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INVESTIGATION OF FLUID BED COMBUSTION OF MUNICIPAL SOLID WASTE

by

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16. ABSTRACT

An experimental study was undertaken to burn processed municipal solid waste in a fluid-bed combustor containing water-cooled tubes in the bed. The 300-hour test was performed without incident and terminated on schedule. The combustor and ducting were clean on inspection after the test, and bed agglomeration did not occur. A corrosion tube placed in the free-board showed considerable metal wastage for carbon and low-alloy steels and some wastage for stainless steels. Low-temperature carbon steel water tubes in the bed showed negligible wastage. It was concluded that heat-exchanger tubes in the freeboard require protection from the high-velocity elutriated solids. Combustion efficiency was greater than 99%, and pollutants were measured as follows. SO_2 = 58 ppm, NO_x = 178 ppm, CO = 242 ppm, Hydrocarbons = 5.4 ppm. A system study was conducted for a co-generation, 800-tons/day power plant to be located on the Stanford U. campus to supply all of the process steam requirement and as much of the electrical power as possible. The size of the plant was determined by the estimated available processed MSW supply in 1983. Preliminary design of components based on the 300-hour test results and cost estimates were made.

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FOREWORD

Today's rapidly developing and changing technologies and industrial products and practices frequently carry with them the increased generation of solid and hazardous wastes. These materials, if improperly dealt with, can threaten both public health and the environment. Abandoned waste sites and accidental releases of toxic and hazardous substances to the environment also have important environmental and public health implications. The Hazardous Waste Engineering Research Laboratory assists in providing an authoritative and defensible engineering basis for assessing and solving these problems. Its products support the policies, programs and regulations of the Environmental Protection Agency, the permitting and other responsibilities of State and local governments and the needs of both large and small businesses in handling their wastes responsibly and economically.

The present study represents a departure for the Stanford High Temperature Gasdynamics Laboratory because the largest part of the effort was subcontracted to an industrial organization. Also long-duration testing was important, and because an economic evaluation of the system was carried further than usual. The subcontracting was performed at the Combustion Power Company of Menlo Park California, where a 7 ft^2 fluid-bed test unit and processing equipment for municipal solid waste were available. The success of this project was in a large measure due to the efforts of the Combustion Power Company.

The project originated at Stanford University, where a combined electrical and process stream load exists and where energy costs are escalating rapidly. The concept of municipal solid-waste combustion in a fluid-bed boiler with cogeneration of electrical power and process heat was suggested. The two major questions appeared to be the performance of the fluid-bed combustor with tubes in the bed and the economics of the system. The present investigation was undertaken to address these questions.

David G. Stephan, Director
Hazardous Waste Engineering Research Laboratory

Abstract

An experimental study was undertaken to burn processed municipal solid waste in a fluid-bed combustor containing water-cooled tubes in the bed. MSW, processed to pass through a two-inch screen, was pneumatically fed at one point into a 7 ft^2 fluid bed. Two 50-hour runs were made to check out the system and to determine a satisfactory operating point for the principal experiment of 300 hours' duration. The test conditions were:

superficial velocity = 4.5 ft/sec

bed temperature = 400 F

freeboard temperature = 1500 F

excess air = 44%

internal recycle of elutriated solids to bed

The 300-hour test was performed without incident and terminated on schedule. The combustor and ducting were clean on inspection after the test, and bed agglomeration did not occur. A corrosion-erosion tube placed in the freeboard showed considerable metal wastage for carbon and low-alloy steels and some wastage for stainless steels. Low-temperature carbon-steel water tubes in the bed showed negligible wastage. It was concluded that heat-exchanger tubes in the freeboard require protection from the high-velocity elutriated solids. Combustion efficiency was greater than 99%, and pollutants were measured as follows.

SO_2	58 ppm
NO_x	178 ppm
CO	242 ppm
Hydrocarbons	5.4 ppm

A systems study was conducted for a co-generation, 800-tons/day power plant to be located on the Stanford University campus to supply all of the process steam requirement and as much of the electrical power as possible. The size of the plant was determined by the estimated available processed MSW supply in 1983. Preliminary design of components based on the 300-hour test results and cost estimates were made. It was estimated that the total plant investment for the co-generating plant, 6.7 MWe average and 200,000 pounds per hour of steam average, would be 23.1 million dollars, exclusive of fuel processing and transportation costs.

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1.0 INTRODUCTION

A concept which utilizes fluid-bed combustion of municipal solid waste has been suggested for application to the power generation and steam supply at Stanford University. Preliminary investigation of the system has shown considerable economic promise, although the operation of an atmospheric fluid bed containing steam-generating tubes had not been tested. Therefore, a program was recommended to the Department of Energy and the Environmental Protection Agency which would involve an experimental program to burn solid waste in a fluid-bed combustor and to undertake a more detailed economic study.

An experimental program was designed to investigate the favorable operating regimes for a bed with steam-raising tubes, to determine the combustion efficiency, to measure the gaseous pollutants, to determine the erosion or corrosion of the tubes, and to investigate the fouling of the tubes or system internals caused by the combustion of municipal solid waste. Two 50-hour preliminary experiments were run in order to shake down the equipment and to conduct a parametric study to specify the most favorable operating regime for a subsequent 300-hour test. All of these experiments were conducted in a 7 ft^2 atmospheric fluid bed located at the Combustion Power Company (CPC) in Menlo Park, California.

An economic study was also undertaken to determine the promise of the system as defined from the results of the experiments. As described below, a complete system was envisaged for application to the Stanford University campus, and the sizing and performance of the fluid-bed, solid-waste combustor was based on the experimental results. The application to Stanford University was used only as a specific application and was not necessarily the most favorable one, because of the wide variety of requirements for electric power and steam. However, it was felt that this would be a typical situation and that there would be considerable benefit in having a study made to meet definite, realistic requirements.

In the report which follows, the proposed system at Stanford University is first described, followed by the results of the fluid-bed testing program. The last section of the report is a presentation of the systems study showing the performance and economics of a fluid-bed, municipal-solid-waste combustion system which incorporates electrical power generation with process heating.

2.0 PROPOSED SYSTEM

In order to prevent the present study from becoming an academic exercise, a practical possible application was defined so that the experimental program would be conducted under realistic test conditions and the economic study would have reference to a specific situation. Therefore, consideration was given to the energy requirements of Stanford University. This is a particularly favorable situation, inasmuch as the University has a central steam-heating system and an electrical power requirement. At the present time the electrical power is supplied by the local utility, and steam is generated in the University's boiler system with natural gas as the fuel, backed up by light fuel oil. The balance of the heating and electrical load is such that co-generation of electricity and process heat is feasible and very attractive from a technical point of view.

The general concept for the Stanford Solid-Waste Energy Program (SSWEP) is to process solid waste at a convenient collection site, where some landfill is available to handle the non-combustible part of the stream. The lightly processed solid waste, which would be processed only so that it can be fed into the combustors through a 5"-diameter pipe, would be transferred to the University campus with special transfer trucks. The size of the system is specified by the available Municipal Solid Waste (MSW), which is estimated to be 800 tons of processed MSW per day in 1983. This corresponds to approximately 1200 tons per day of raw MSW delivered to the remote processing site. The plan would be to feed the processed MSW to fluid-bed boilers, which would be built in a modular fashion for economy and for improved turn-down as required for meeting the variable load on the campus. Superheated steam at a modest pressure and temperature would be delivered to a steam turbine, with extraction at a pressure of approximately 170 psia. The extraction steam would condense in a heat exchanger and then be returned to the fluid-bed boiler. The heat exchanger would transfer heat to the return condensate from the Stanford heating system to produce 140 psia steam for the Stanford system. If all of the flow from the high-pressure turbine was not required for the heat exchanger, the remainder would flow to a condensing turbine in order to generate more electrical power. A cooling tower would be provided for cooling the condenser so that the fluid-bed boiler steam would be self-contained and could be carefully controlled.

The fluid-bed boiler system involves a combustion air blower, an air preheater, and an exhaust clean-up system after the fluid-bed boiler. The solid waste would be introduced into the bed pneumatically, and the present design incorporates internal recycling of elutriated flyash and bed material to the bed, as this was found beneficial in the experimental program. Most of the system is conventional, with the fluid-bed boiler being the most novel and at the same time the most critical component. Because of this, an experimental

program was performed in a 7 ft^2 fluid-bed combustor with water-cooled tubes. Air-cooled tubes were included for corrosion tests in both the freeboard and in the active bed, in which test samples were subjected to the expected temperature of superheater tubes in an actual application.

A flow diagram of the plant which was studied and for which a preliminary cost estimate was made is shown in Fig. 1. In this diagram can be seen the schematic representation of the MSW feed, the fluid-bed boiler system, and the steam-turbine system for generating electrical power along with the process heat exchanger. No attempt was made to investigate the processing of the MSW, because the present study was limited entirely to the conversion of the processed MSW to thermal energy and to electricity. The North Santa Clara County Joint Exercise of Powers Agreement (JPA), the state-sponsored agency which handles municipal solid waste in the Stanford Univesity area, has made studies of waste disposal, and they have concluded that, next to landfill, processing solid waste to Refuse-Derived Fuel (RDF) is the most economical disposal technique. Potential users of the RDF, while not yet identified, include Stanford University and the Pacific Gas & Electric Company, which plans to construct a coal-fired plant about 100 miles to the north in 1986. It should be recognized that, if the Stanford University program involving a fluid-bed combustor goes forward, the processing of the municipal solid waste can be simplified to the degree that the material can be pneumatically fed through 5" lines. At the time of preparation of this report, no decision had been made by either the North Santa Clara County JPA or by the University concerning firm plans for MSW availability or type of energy system for the campus.

The major effort of this investigation was to undertake an experimental determination of the combustion of processed MSW in a fluid boiler containing water-cooled tubes. This investigation is described in the next section.

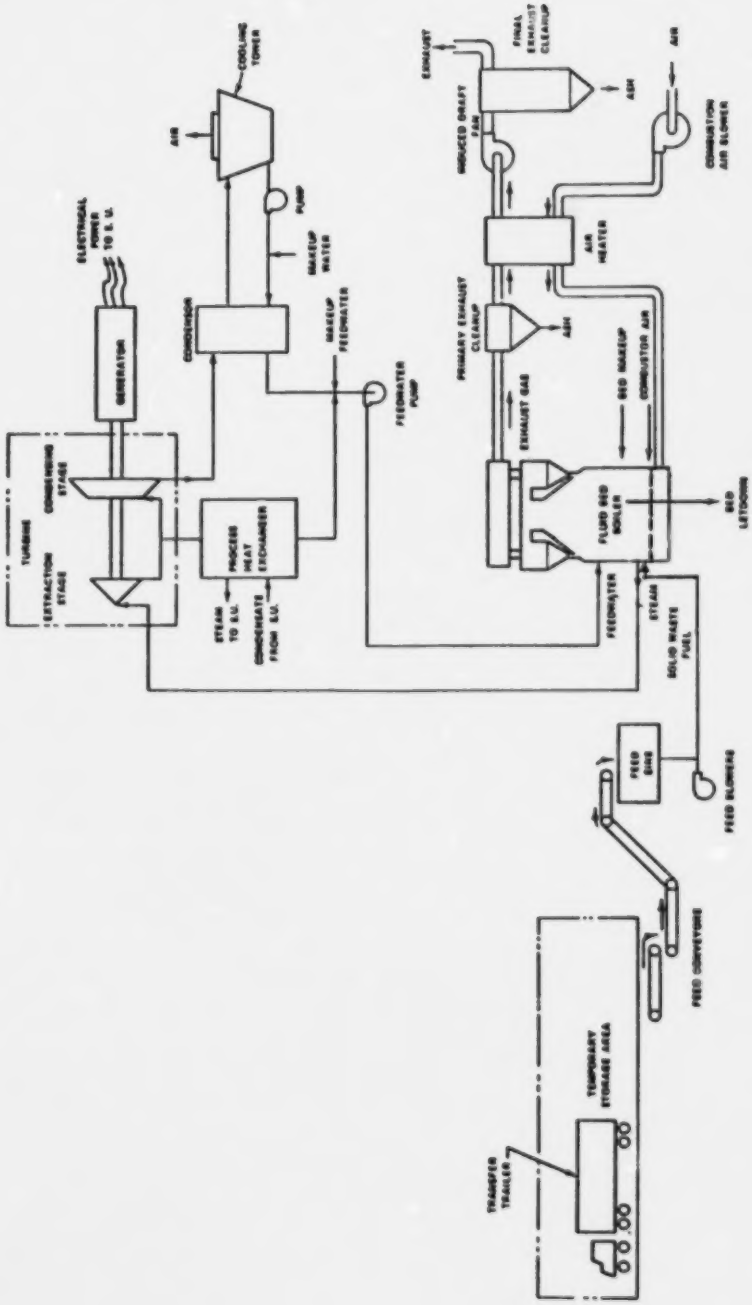

Figure 1. Stanford solid waste energy plant flow diagram.

3.0 FLUID-BED TEST PROGRAM

A test program was designed to check out the equipment, to determine a favorable operating point for the 300-hour test, and then to conduct a 300-hour continuous test to investigate long-term performance of the system. The equipment check-out test and the parametric test were nominal 50-hour tests. This section of the report describes the equipment and the two 50-hour tests, SSWEP #1 and SSWEP #2. The section concludes with a description of the 300-hour test, SSWEP #3.

3.1 EQUIPMENT DESCRIPTION

3.1.1. Fluidized-Bed Combustor

SSWEP testing was conducted in a 7 ft^2 atmospheric fluidized-bed combustor at the Combustion Power Company. The refractory lined combustor, called the Customer Test Unit (CTU), is cylindrical, with an inside diameter of 3 feet and an inside height of 16 feet. The CTU is designed to permit several different fuel-feed and heat-extraction arrangements. A viewport permits observation of the bed during operation. Figure 2 shows the CTU facility, as arranged for combustion of processed Municipal Solid Waste (MSW). The oil-fired air heater is used only during startup of the combustor; all tests were conducted without preheated air.

The heat-exchanger arrangement for the SSWEP 300-hour test is shown schematically in Fig. 3. The two horizontal four-pass tubes are piped in series and are considered a single exchanger, with a heat-transfer area of 9.46 ft^2. The vertical tube is a small two-passcoil with an area of .96 ft^2. It is incorporated to provide the total of 10.42 ft^2 heat-transfer surface theoretically necessary to achieve the desired operating point.

Heat is transferred to the fluid-bed tubes by heating pressurized water below saturation. Typically, 150 psig water is heated from 200 F to 300 F, and the 300 F water is then dropped to atmospheric pressure across a valve. Some of this water flashes to steam, bringing the remaining water to 212 F. Make-up water to the system then reduces the recycled water temperature to about 200 F. The water-tube wall temperatures are much lower than those of typical boiler tubes; consequently, temperature-related corrosion does not occur.

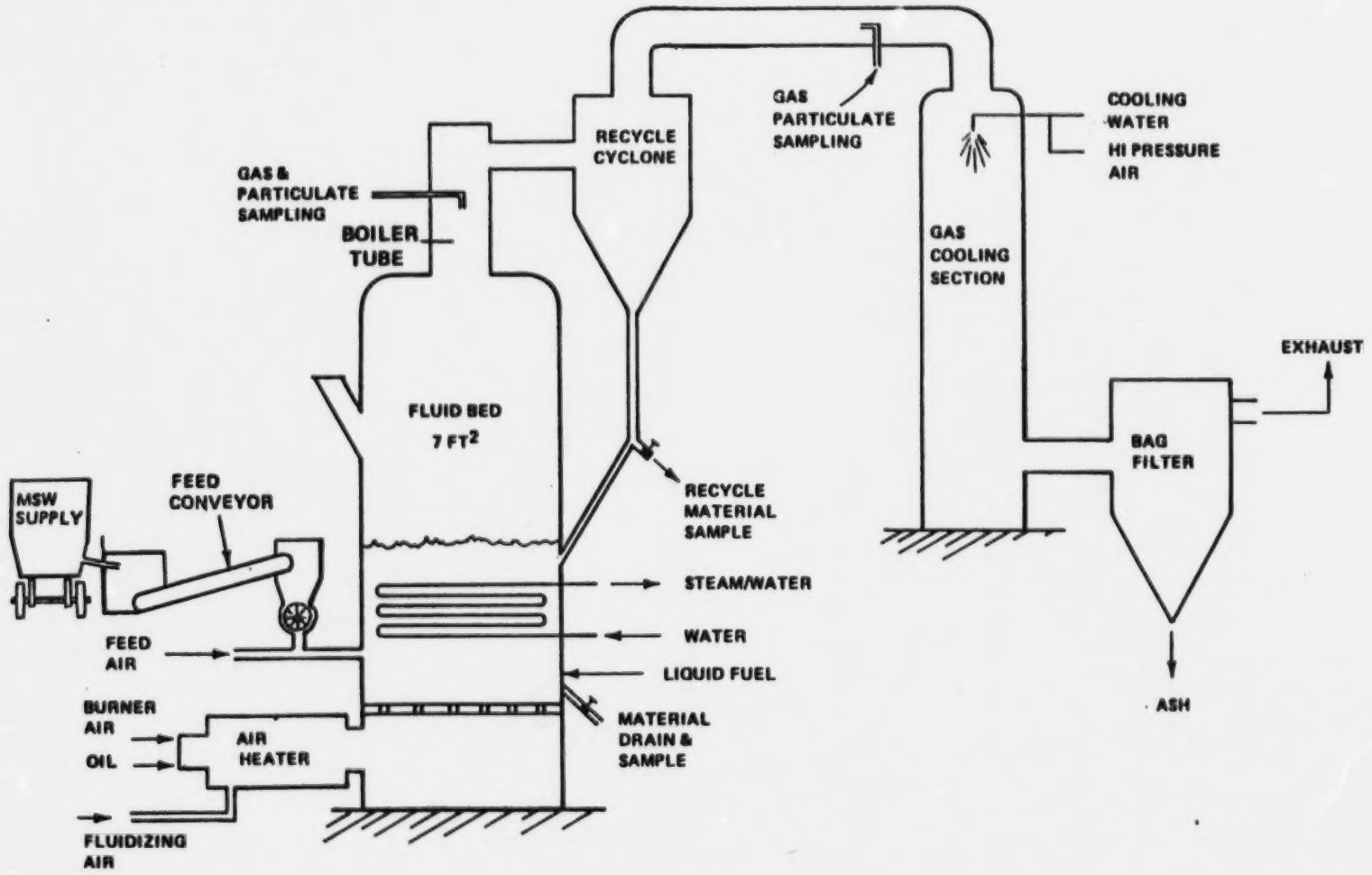

Figure 2. Fluid-bed boiler test facility.

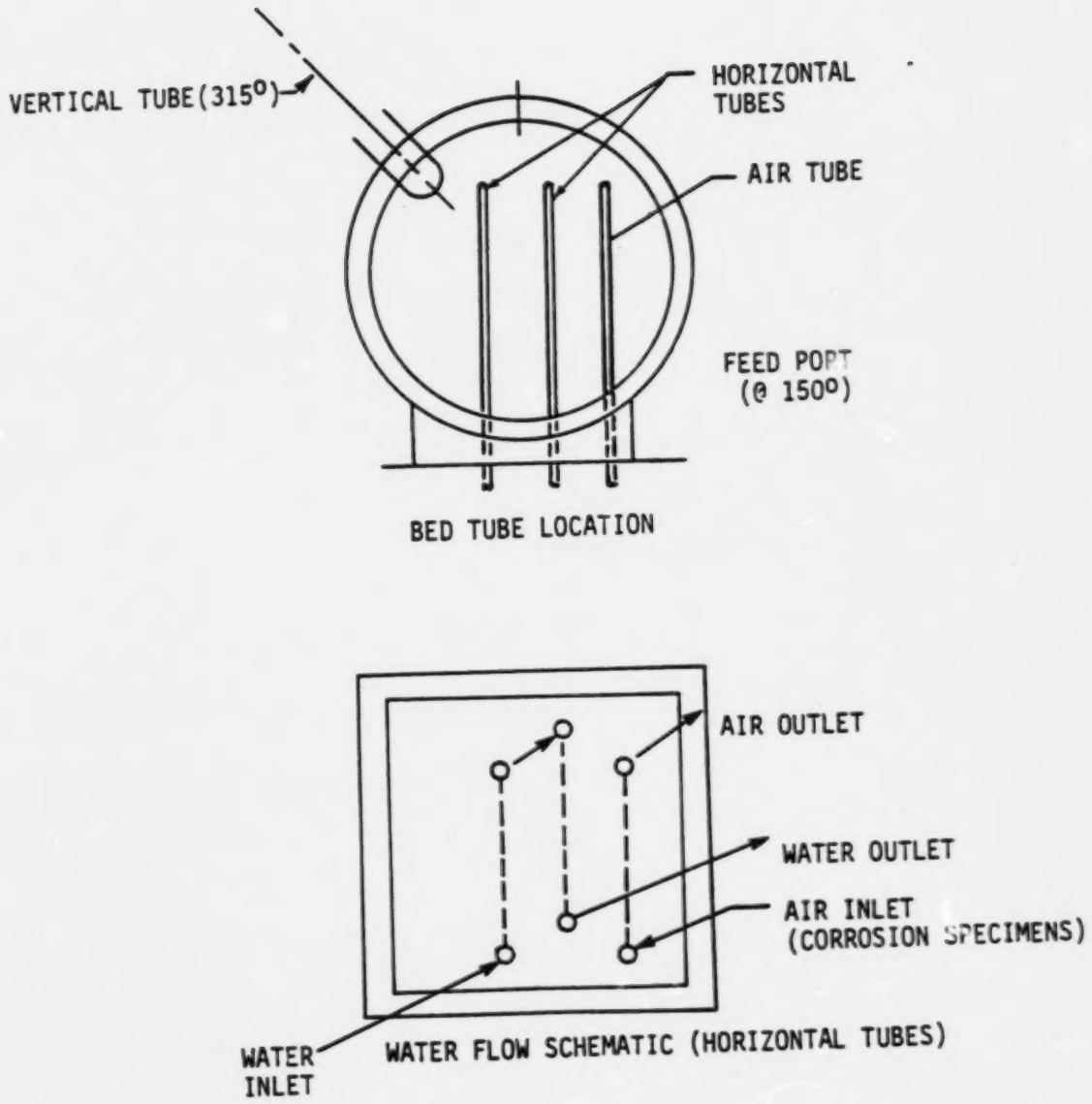

Figure 3. SSWEP 300 hour test bed heat exchanger arrangement.

Air-cooled sample tubes are installed in the fluid bed and in the freeboard. These tubes are designed to duplicate boiler and superheater tube-wall temperatures for study of erosion and corrosion.

The combustor may be operated with or without recycle of exhaust particulates to the bed. Discharge piping from the stainless-steel recycle cyclone permits sampling of recycle material during operation. For SSWEP #1, the cyclone at the combustor was arranged to bypass the recycle feature by connecting the cyclone drop leg directly to an ash-collection barrel. For SSWEP #2, the cyclone was arranged to recycle elutriated material back to the combustor. The 300-hour test was conducted with the recycle system in operation.

Exhaust gas from the recycle cyclone passes through a spray cooler before final particulate clean-up in a baghouse. Stack discharge from the baghouse meets all applicable emissions regulations. Sampling ports are provided before and after the recycle cyclone and also in the discharge stack from the baghouse.

3.1.2 Solid Waste Preparation and Feed

CPC has an existing solid-waste processing facility which was made available for the preparation of fuel for the Stanford program. Municipal solid waste was received in conventional packer trucks, each containing between 3 to 6 tons of refuse. These trucks dumped their contents onto a covered concrete pad, and the refuse was pushed onto the shredder input conveyers. A 100-hp Eidal mini-mill shredder with a nominal capacity of 5 tons/hour was used. However, the actual shredder throughput was about 1-1/2 tons/hour for the present program.

The shredder solid waste was air-classified and the light fraction pneumatically transported to a storage shed, as shown in Fig. 4. The RDF was then loaded into drop-bottom bins and transported to the CTU facility by forklift via the route shown in Fig. 4.

At the CTU, the RDF was transferred to a live-bottom trailer which provided storage and controlled outfeed capability. A metering conveyer with precise volume control transferred RDF from the trailer to the combustor feed system on demand, as dictated by a fluid-bed temperature-control loop. The metered fuel was then transferred to a constant-speed, rotary-air, lock-feeder valve, from which fuel was pneumatically transported to the combustor fluid bed via a 3-inch feed pipe.

3.1.3 Instrumentation

During combustion of processed MSW, temperatures in the system were monitored at 37 points. Data were collected for pressure and flow of combustion air, exhaust gas, cooling air and water, and fuel oil. Exhaust gas composition was continuously monitored, and concentrations of O_2, CO_2, NO_x, SO_2, CO, and hydrocarbons were recorded. Gas analysis was supplemented by Orsat

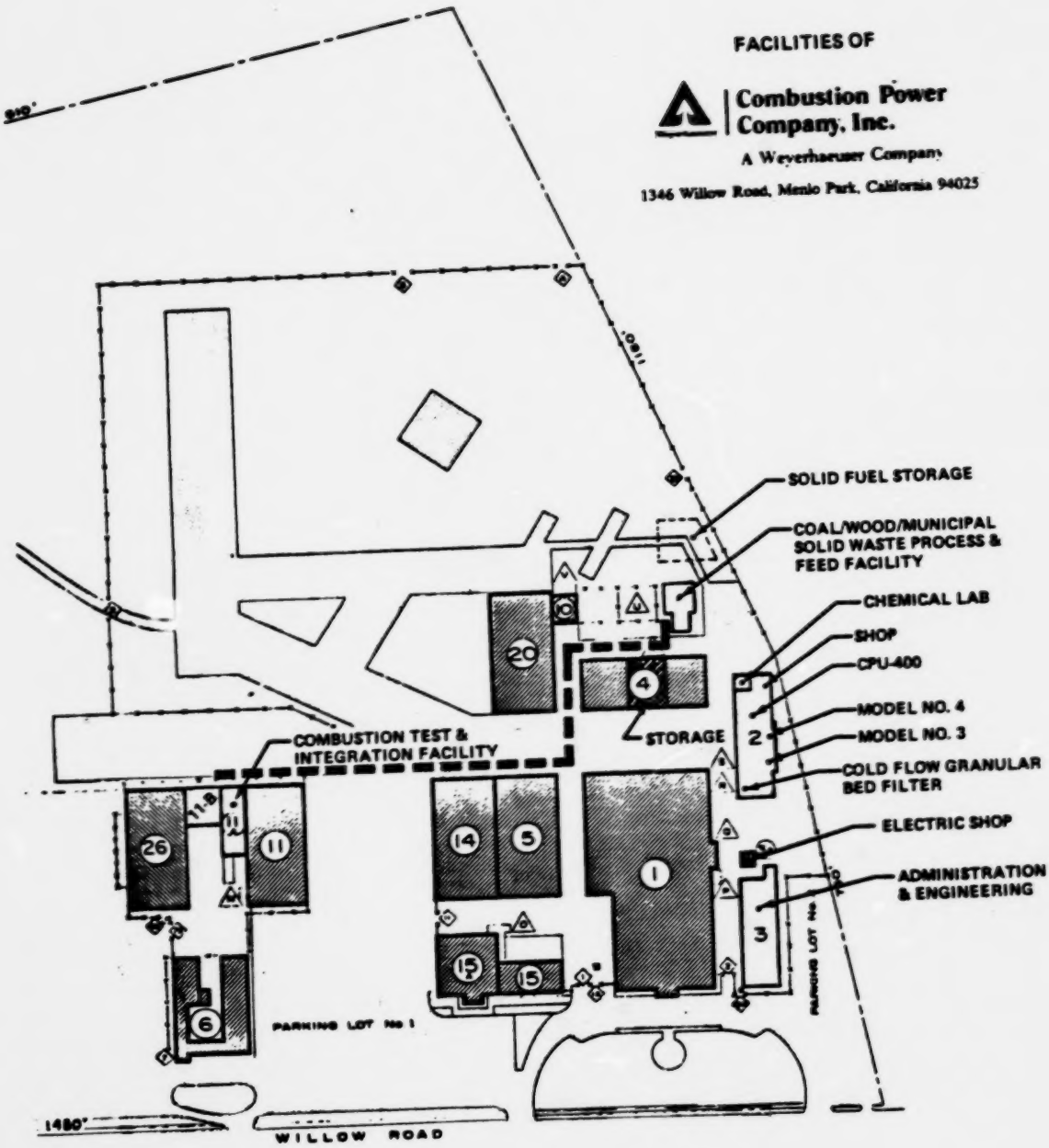

Figure 4. RDF transfer route.

testing at frequent intervals. Samples were taken daily for determination of HCl concentration and particulate loading.

3.2 FIFTY-HOUR TESTS

3.2.1 Test Plan

Two 50-hour tests (SSWEP #1 and #2) were conducted to determine the fluid-bed combustion characteristics, with heat extraction from the bed and from the exhaust while burning RDF. The test set-up for each differed in configuration, SSWEP #1 being conducted without cyclone separation recycle to the combustor, and SSWEP #2 being conducted with recycle.

The basic test plan was identical for both tests, and an operational envelope was developed to identify desired test points at 4 to 8 fps superficial velocity and 20% to 80% excess air. Figure 5 shows the proposed operating envelope and planned test points. The graph shows that, at any particular excess air, superficial velocity is directly proportional to bed heat-exchanger area. The vertical dashed lines define the various heat exchanger areas available in the bed. Heat-exchanger area was available only in finite steps as the operator selectively shut off individual exchanger tubes. The areas available were 9.26 ft^2, 13.99 ft^2, 18.52 ft^2, and 22.92 ft^2. For SSWEP #2, arrangements for 22.92 ft^2 were not included.

3.2.2 Test Objectives

The objectives of these tests were to:

- Explore the limits of operational parameters, such as excess air and superficial velocity.
- Determine combustion efficiency within the limits determined above.
- Determine the extent of deposition or clinker formation in the combustor and downstream equipment, including an exhaust heat exchanger.
- Determine operational stability in maintaining bed and freeboard temperatures under varying heat-extraction conditions.
- Determine the effect of recycle on system operation, deposition control, heat transfer, and combustion efficiency.
- Determine the characteristics of the exhaust-gas emissions.
- Confirm expected heat-transfer coefficients for the fluid-bed heat exchanger and the exhaust-duct heat exchanger.

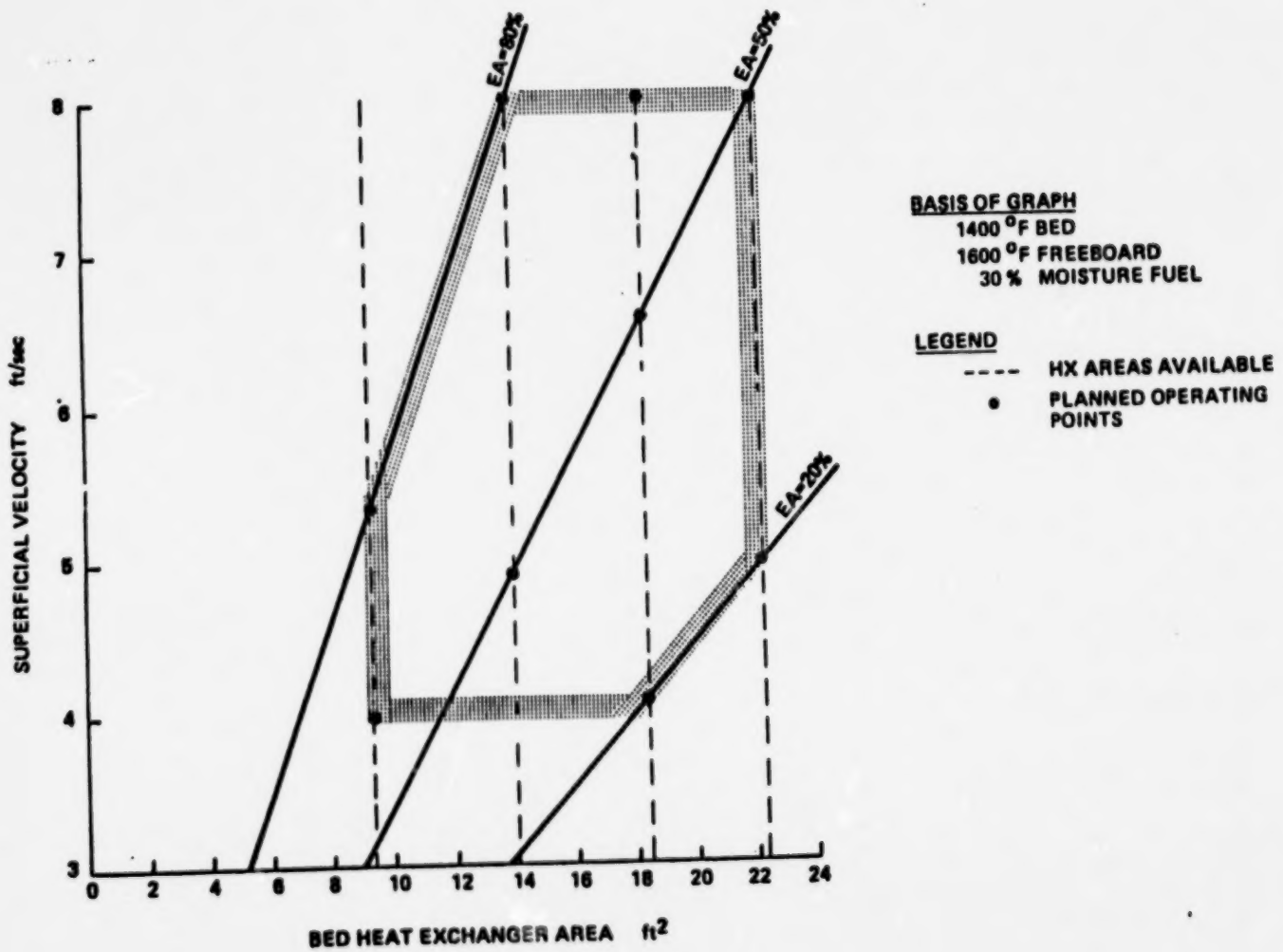

Figure 5. SSWEP parametric tests operating points.

3.2.3 Test Summary

SSWEP #1

SSWEP #1 was the first 50-hour solid-waste combustion test. The cyclone in Fig. 2 was arranged for ash collection only, i.e., without recycle of the separator fines to the combustor. The objective of this test series was to determine steady-state combustion performance at predetermined setpoints between 20% and 80% excess air, 4 to 8 fps superficial velocity, and 1400 F bed temperature.

SSWEP #1 began on April 25, 1979, when solid-waste combustion was established after preheating the combustor. This test failed to achieve prolonged steady-state conditions due to feedline plugging problems. The majority of these plugs occurred because round, plastic lids of 3-in. or larger diameter jammed in the transition section to the 3-in. feed pipe used to pneumatically transport fuel to the combustor. These lids passed through the solid waste shredder unharmed and typically did not drop out of the air classifier. Other plugs occurred due to occasional variations in the physical properties of the solid waste. One factor was high fuel moisture content caused by intermittent rain during the week of testing, which resulted in periodic feedstock agglomeration. Fuel-handling and feed equipment were not weather-protected.

It was discovered that, despite the feedline-plugging problems, fairly even temperatures could be maintained throughout the combustor. However, O_2, CO, CO_2, and HC_x fluctuated over wide ranges. The accumulation of deposits in the flue-gas ducting in the vicinity of the cyclone caused a shutdown after a total of 48 hours of solid-waste combustion, due to a high freeboard pressure.

SSWEP #2

The test configuration for SSWEP #2 differed from that for SSWEP #1 in that the hot-gas cyclone was arranged to recycle elutriated solids back to the combustor. The test conditions were similar to SSWEP #1, except that the limits on excess air were changed to 50-80%.

After a normal heat-up, solid-waste combustion began on May 7, 1979, with shutdown occurring on May 10, after 73 hours on solid waste. Feed-system modification eliminated feedline plugging as a problem; however, the recycle system was inoperative during most of the test, due to cyclone/dipleg plugging.

Except for the first test point, combustion appeared much improved over SSWEP #1. Fluid-bed temperatures were generally higher and afterburning lower. Improved combustion was attributed to the following conditions:

- Higher excess air combustion than SSWEP #1;
- Drier solid waste during SSWEP #2 due to warmer and drier weather;
- Smoother fuel feed to the combustor.

SSWEP Parametric Test Results

During the periods of stable operating conditions of SSWEP #1 and #2, the following results apply:

- Stable bed combustion was maintained with a 3-ft.-deep bed over the ranges of:

Bed Temperature (F)	1300 - 1410
Superficial Velocity (ft/sec)	4.1 - 6.8
Excess Air (%)	50 - 74

- Combustion efficiency was generally 98.5 - 99.3%, averaging 98.9% with excess air at 50% or higher.

- Operation with excess air below 40% resulted in significant afterburning and ash deposits in freeboard.

- Hydrocarbon emissions ranged from 15 ppm to 130 ppm.

- Carbon monoxide emissions ranged from 30 ppm to 540 ppm.

- Processed MSW Properties:

	Average	Range
Moisture Fraction (%)	28.1	15.9 - 37.8
Ash Fraction (%)	14.7	10.9 - 20.4
Volatile Fraction (%)	72.0	64.6 - 78.5
Fixed Carbon Fraction (%)	9.89	6.28 - 12.3
Higher Heating Value (Btu/lb)	7106	6859 - 7538
Sulfur (%)	0.19	0.15 - 0.24
Chlorine (%)	0.23	0.15 - 0.35

- In-Bed Heat Exchangers Performance:
  Avg. overall HX coefficient was 44.3 Btu/hr-ft^2-F.
  Active heat-exchanger surface area range from 9.26 ft^2 to 22.9 ft^2.
  Post-test inspection showed clean tubes where active bed made contact and thin black deposits on shadowed areas.

- Stack Heat Exchanger Performance:
  Heat transfer coefficient was generally above 10 Btu/hr-ft^2-F.
  Only minor deposits formed on tubes.
  Loose particulate material partly filled the heat exchanger chamber.

3.2.4 Analysis of Test Results

Baseline Operation Envelope

Based on the results obtained with tests SSWEP #1 and SSWEP #2, a new baseline operating envelope can be superimposed on the parametric plot (Fig. 5) showing the "SSWEP Parametric Tests Operating Points." Figure 6 illustrates this operating envelope with a favorable operating region for SSWEP #1 and SSWEP #2 between superficial velocities of 4 to 7 fps and excess air greater than 50%.

The barrier between favorable and unfavorable operation is loosely defined. Design changes to the fluid bed, beyond the scope of this program, could extend the favorable operating region.

Operation at all the desired setpoints, also shown in Fig. 6, was not quite achieved, for several reasons. Combustion at excess air lower than 50% was characterized by bed temperatures lower than 1400 F and/or freeboard temperatures higher than 1600 F. For example, a test point at 11% excess air and 22.92 ft^2 of bed heat-exchanger surface at 5.9 fps superficial velocity was performed with a bed temperature of 1247 F and a freeboard temperature of 1742 F, with fuel moisture at 15.1%. These parameters do not even come close to matching the basis of the graph, which is a 1400 F bed and 1600 F freeboard with 30% fuel moisture. Conversely, the actual point at 51.3% excess air with 13.99 ft^2 of heat exchanger at 5.0 fps should be noted. This point is close to the desired setpoint at 4.9 fps and 50% excess air. The bed temperature was actually 1386 F, freeboard temperature 1597 F, and fuel moisture 27.2%.

The test also revealed that combustion at high superficial velocities was characterized by high freeboard temperatures caused by high afterburning. High freeboard temperatures are undesirable because of the low melting point materials known to exist in the ash. Generally, the operators tried to stay below 1600 F in the freeboard, but this was extended to 1650 F in order to obtain some data at low excess air and/or high superficial velocity. Still, some data points, especially in the SSWEP #1, exceeded the 1650 F freeboard limit. During actual operation, the test conductor would increase combustor airflow and move up a constant heat exchanger line until the freeboard temperature reached the 1650 F limit.

Temperature Stability and Distribution

Table 1 shows a tabulation of the six test points from SSWEP #1 and the five test points from SSWEP #2. Excess air tabulated for SSWEP #1 was calculated from the gas-analyzer data. For SSWEP #2, the gas analyzers were biased by sample-line air leakage for point 2-5. At point 5, SSWEP #2, the Orsat analyzer was used to determine excess air. These data were then correlated with results from fuel ultimate analysis and heating values during SSWEP #2. With the fuel-heating value, ultimate analysis, fuel moisture, air flow, system temperatures, and bed heat transfer known, the computer program for solid-waste-combustion data reduction was used to calculate excess air.

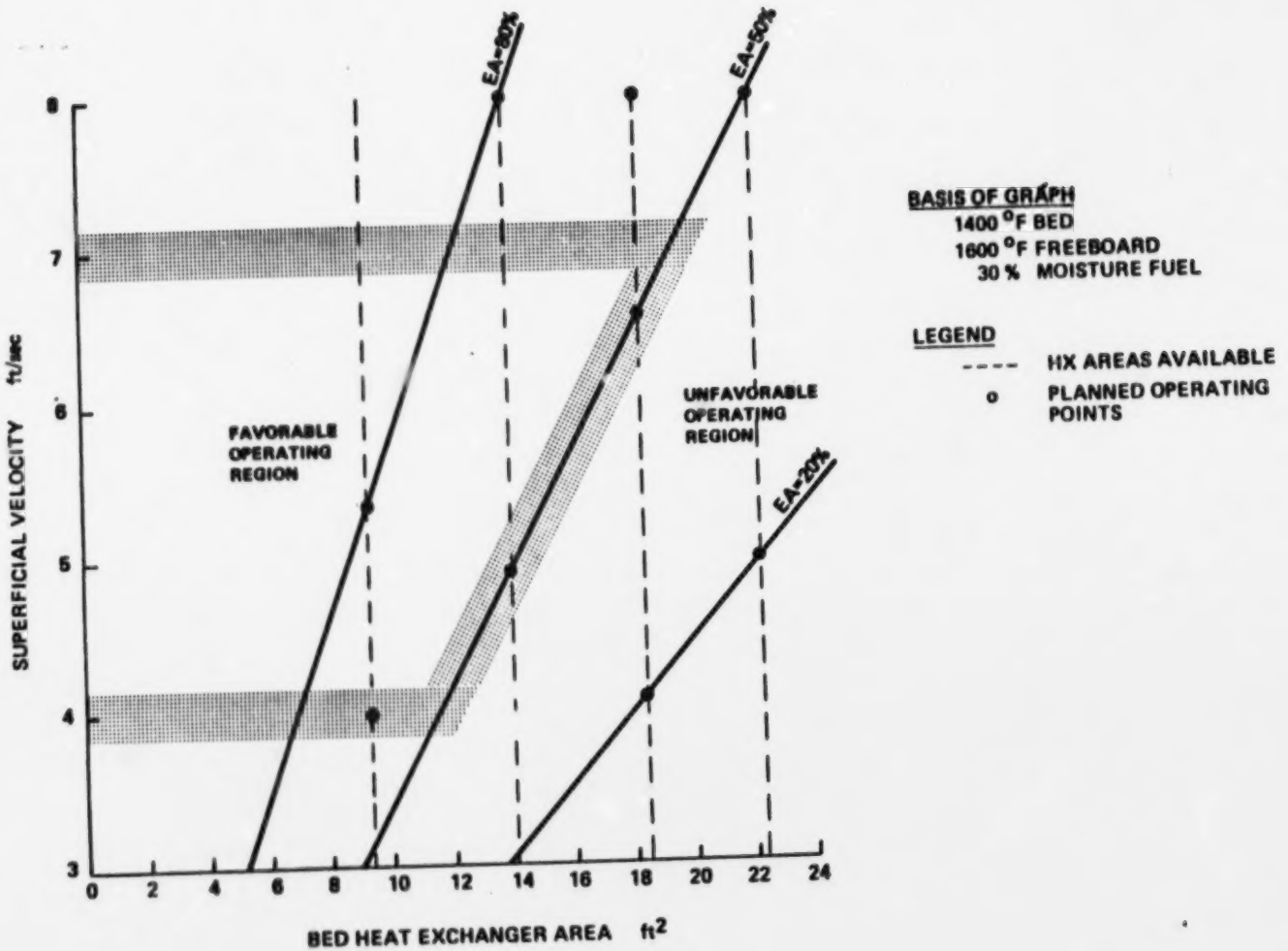

Figure 6. Solid waste combustion operating regions.

Table 1

TEMPERATURE STABILITY AND DISTRIBUTION

SSWEP	Point	Date	Time	Comb. Air (SCFM)	Superficial Velocity (fps)	Excess Air (%)	Freeboard Press (IWG)	Temperatures Bed (°F)	Freeboard (°F)	Cyclone In (°F)	Cyclone Out (°F)	Exchanger Exhst.(°F)
1	1	4/25/79	1120	928	7.2	26.6	10	1325	1563	1710	1564	879
1	2	4/25/79	1800	793	5.9	11.0	12	1247	1561	1742	1515	889
1	3	4/25/79	2000	806	6.1	34.1	11	1304	1605	1735	1440	842
1	4	4/26/79	1900	784	5.4	53.3	52	1296	1584	1271[a]	1425	882
1	5	4/27/79	0700	863	5.4	53.1	95	1277	1610	1390[a]	1497	917
1	6	4/27/79	0800	863	5.2	b	92	1193	1452	1590	1282	828
2	1	5/8/79	1530	900	6.8	65[d]	14	1307	1387	1674	1500	891
2	2	5/9/79	1600	815	6.6	74[d]	10	1392	1514	1557	1374	847
2	3	5/9/79	2000	625	5.0	51[d]	8	1386	1597	1627	1398	818
2	4	5/10/79	0100	471	3.8	29[d]	5	1368	1608	1619	1384	773
2	5	5/10/79	1700	501	4.1	65.9[c]/63.5[d]	6	1411	1501	1473	1237	722

Notes: (a) Thermocouple became buried in ash and gave abnormally low readings. (b) Not recorded
(c) Orsat analysis. (d) Calculated (gas analysis equipment inoperative).

Locations of the combustor thermocouples are shown in Fig. 7. Bed temperature was taken as an average of the bed thermocouples.

Combustion Efficiency

Table 2 presents the operating data used to define the combustion efficiency. For SSWEP #1 the fuel properties varied significantly during the test. For this reason the fuel moisture contents and heating values are tabulated for each point. Heating values are reported on a dry, ash-free basis. During SSWEP #2, fuel conditions remained more constant; therefore, the moisture content and heating values were averaged and used for all points. The heating value for SSWEP #2 is actually the average of the CPC-determined heating value and those determined by Commercial Testing and Engineering Company. Reports from these sources are contained in Appendices A and B for SSWEP #1 and SSWEP #2, respectively.

Excess air for SSWEP #1 was calculated from gas-analyzer data and fuel composition by the procedure outlined below.

- Excess Air (SSWEP #1)

The formula used to calculate excess air for SSWEP #1 is based on theoretical combustion relations.

$$EA = \frac{2.67C}{2.67C + 8H + S - O} \times \frac{O_2}{CO_2 + CO} \times 100\% \ .$$

where:
- EA = Excess Air (%),
- C = Carbon, dry weight %,
- H = Hydrogen, dry weight %,
- S = Sulfur, dry weight %,
- O = Oxygen, dry weight %,
- O_2 = Oxygen, dry volume %,
- CO_2 = Carbon Dioxide, dry volume %,
- CO = Carbon Monoxide, dry volume %.

Average concentrations of C, H, O, and S were used to give

$$EA = k \frac{CO_2}{CO_2 + CO} \quad \text{where} \quad \begin{array}{l} k = 93.7 \text{ for SSWEP 1 \& 2} \\ k = 89.8 \text{ for 300 hour test} \end{array}$$

where k = 93.7 for SSWEP 1 and 2, and k = 89.8 for the 300-hour test. For SSWEP #2 the gas-analyzer module gave erroneous flue-gas concentrations for points 2, 3, 4, and 5. As described earlier, the excess air was back-calculated using the Orsat-determined data at point 5 in addition to knowledge of the fuel properties and the operating conditions.

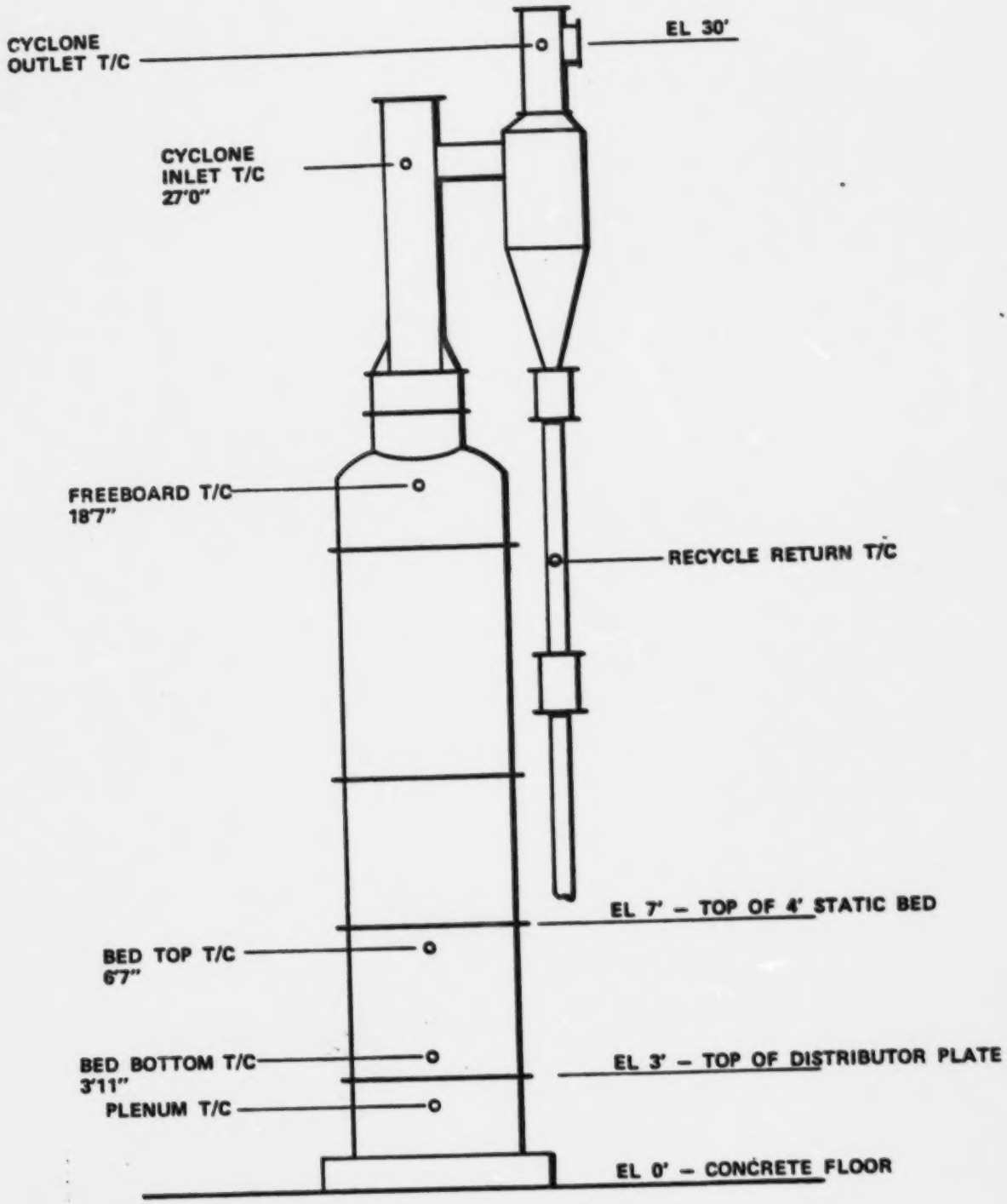

Figure 7. CTU combustor thermocouples.

Table 2

SOLID-WASTE FEED AND FLUE-GAS CHARACTERISTICS

SSWEP #1 Point	(Total) Comb. Air Flow (SCFM)	Super-ficial Velocity (fps)	H_2O (%)	HHV Btu/lb	Feed Rate Lb/min (wet)	Excess Air (%)	CO (ppm)	CH_x (ppm)	η Combustor	FBD Pressure (IWG)
1	928	7.2	15.9	8191	12.0	26.6	250	80	98.8	10
2	793	5.9	24.6	9137	12.0	11.0	106	180	98.6	12
3	806	6.1	23.1	8365	12.0	34.1	>1000	300	98.1	11
4	784	5.4	37.8	8286	13.5	53.3	40	130	98.9	52
5	863	5.4	35.6	8701	12.5	53.1	165	40	99.0	95
6	863	5.2	36.0	8701	12.0	c	300	40	99.0	92
SSWEP #2										
1	900	6.8	27.2	8242	11.0	40.5	480	15	98.9	14
2	815	6.6	27.2	8242	9.5	74	30	40	98.9	10
3	625	5.0	27.2	8242	8.5	51	120	60	98.6	8
4	471	3.8	27.2	8242	8.0	29	2100	80	95.6	5
5	501	4.1	27.2	8242	6.0	65.9[a]/64[b]	540	15	99.3	6

(a) ORSAT analysis. (b) Calculated (adjusted) values. (c) Not recorded.

The combustion efficiency is calculated using the procedure defined below.

- Carbon Combustion Efficiency Technique

  It is assumed that unburned carbon in the flue gas will exist in the forms of CO, HC (hydrocarbons), and C (elemental carbon) only. Therefore, combustion efficiency may be calculated by the following equation:

$$\eta = \frac{\frac{12}{44} a (\Delta H_{CO_2}) + \frac{12}{28} b (\Delta H_{CO}) + \frac{24}{30} c (\Delta H_{HC})}{\frac{12}{44} a + \frac{12}{28} b + \frac{24}{30} c + d \quad \Delta H_{CO_2}}$$

where:

a = weight concentration of CO_2 in flue gas,
b = weight concentration of CO in flue gas,
c = weight concentration of HC in flue gas, and
d = weight ratio of C to flue gas.

The further simplification of the above equation is based on the assumption that 1 lb of carbon releases 14,087 Btu when converted to CO_2, 3,965 when converted to CO, and about 2000 Btu when forming ethane, C_2H_6, the most likely hydrocarbon in the flue gas. Hence,

$$\eta = \frac{\frac{14087}{44} a + \frac{3965}{28} b + \frac{(2)(2000)}{30} c}{\frac{a}{44} + \frac{b}{28} + \frac{2c}{30} + \frac{d}{12} \quad 14,087}$$

or

$$\eta = \frac{a + 0.442b + 0.416c}{a + 1.571b + 2.933c + 3.667d}$$

Deposition

The location of the deposits resulting from solid-waste combustion are shown in Figs. 8 and 9 for SSWEP #1 and SSWEP #2, respectively. During SSWEP #1, deposits presented a very serious problem. The accumulated ash agglomerates built up to a point where the combustor freeboard pressure climbed from the usual 5 to 15 inches water column to 95 inches. It was this situation that forced a shutdown in SSWEP #1.

The severity of the deposit problem was much less in SSWEP #2 in that the vertical ductwork just upstream of the cyclone remained clean as opposed

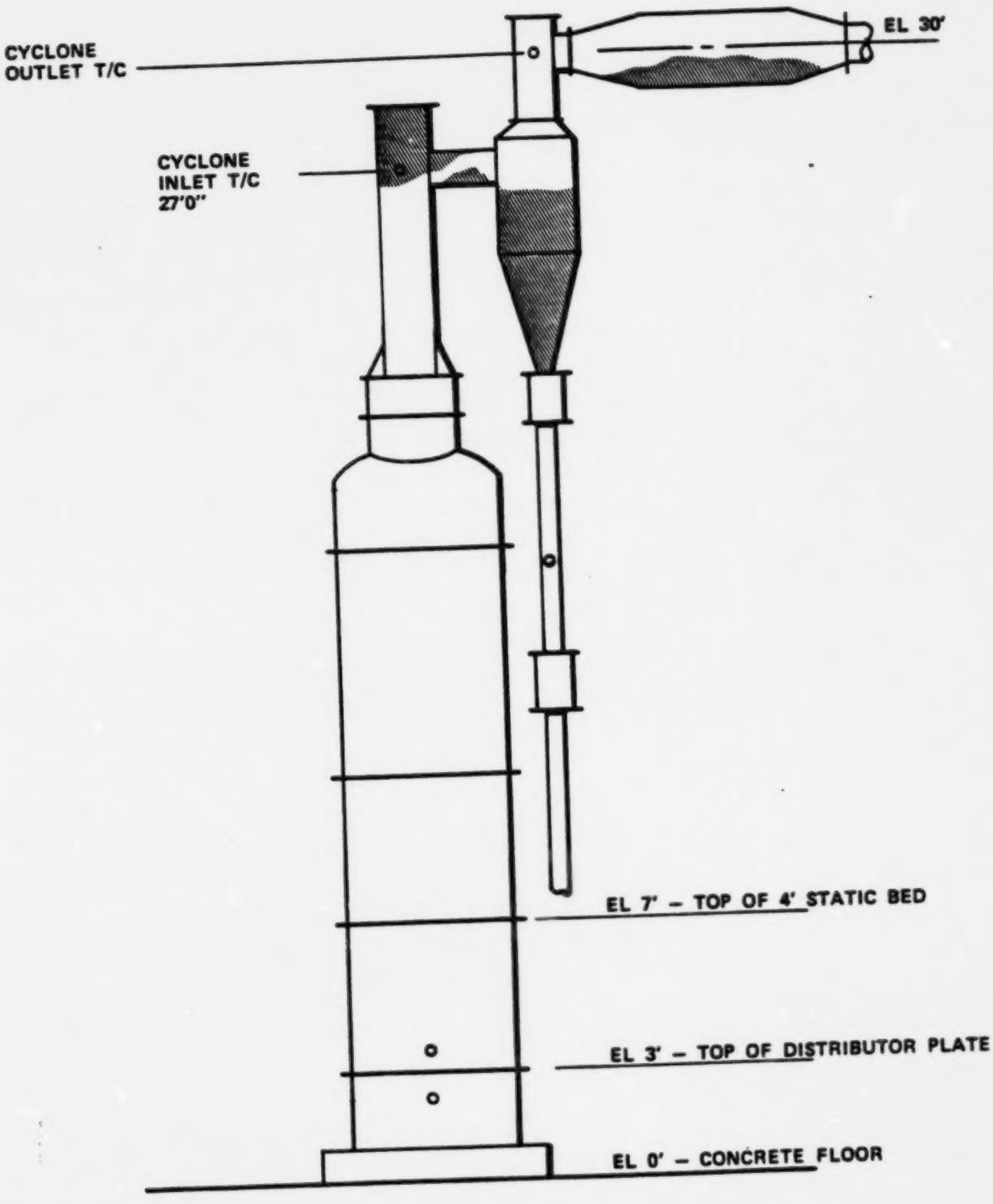

Figure 8. CTU combustor deposit locations - SSWEP #1.

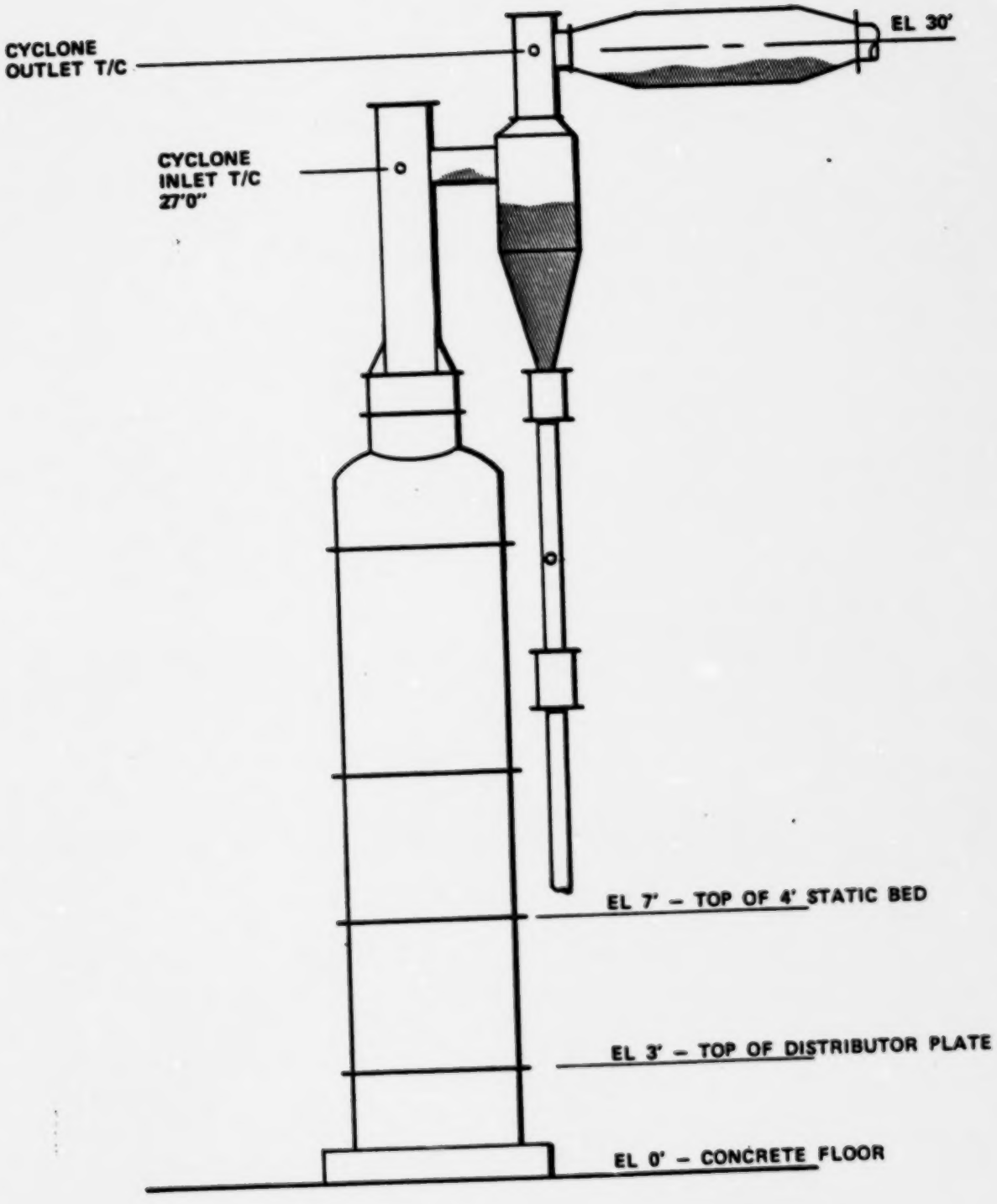

Figure 9. CTU combustor deposit locations - SSWEP #2.

to being packed with agglomerate, as shown by Figs. 8 and 9. Also, the constancy of gas flow and pressure levels indicated that the deposits accumulated in the cyclone up to a certain point.

The deposit problem was not as severe during SSWEP #2 because of the operating mode. First, the freeboard temperature and cyclone inlet temperatures were not as high. Second, during the early part of SSWEP #2, the recycle was functioning intermittently. Experience in previous testing at CPC has demonstrated that deposits (clinkers) in the cyclones are considerably reduced when the recycle is working.

The nature of the deposits in respective locations was similar for both tests, as follows:

- Deposits in the combustor exhaust transition to the cyclone (SSWEP #1 only): hard, sandstone-like chunks of agglomerate with pockets of free-flowing ash and media mixture.

- Deposits in the cyclone: mostly hard, similar to those in the transition to the cyclone above. There was a small amount of hard, shale-like deposits in the cone section of the cyclone.

- Accumulation in the heat exchanger: In the exhaust heat exchanger, the material collected was a loose, free-flowing mixture of ash and media. Actually, it was not a deposit, but more a result of the heat exchanger's acting like a settling chamber. Some soft ash coated the portions of the tubes not buried in the lower third of the heat exchanger.

A laboratory analysis was performed to determine the chemical makeup of the deposit, and to determine whether there was an obvious temperature at which the agglomerate forms.

Fusion-temperature analysis on samples of the hard and soft deposits described in the cyclone above showed initial deformation temperatures of 1990 F and above. The temperature in the combustor or freeboard never exceeded 1750 to 1800 F except for very brief excursions to 1850 F.

A differential thermal analysis (DTA) was run on some of the hard and soft agglomerate samples from the cyclone. The results showed some reaction around 1075 F for both samples, but the laboratory reported that this was not related to the softening or fusion problems encountered. The DTA results showed ash-softening points closely agreeing with the temperatures found in the fusion tests. From this standpoint the DTA revealed no new data.

The results show the major components of the hard and soft ash agglomerates to be as follows:

Major Elements	Weight (%) on Dry Basis	
	Hard Deposit	Soft Deposit
Silicon	21.8	3.3
Alumina	16.0	3.8
Calcium	4.2	4.5
Sodium	2.7	4.9
Potassium	0.98	2.5
Iron	1.10	1.22
Magnesium	0.57	0.52
Lead	0.63	0.37
Titanium	0.26	0.25
Manganese	0.15	0.058
Phosphorous	0.28	0.32

The conclusions drawn from the studies on the agglomerates are as follows:

- Apparently there is a temperature at which the ash agglomerations do not form. The lab analysis did not identify this temperature, yet it is apparent that, as hard deposits were not found in the exhaust heat exchanger or in the ductwork leaving the cyclone, this temperature is in the 1400 to 1600 F region.

- The ash agglomerate does not melt at the same temperature at which it was formed. The fusion temperatures of the ash samples were much higher than temperatures experienced in the ductwork and cyclone.

Heat Exchanger Coefficients

Fluid Bed Heat Exchanger Coefficients

Heat exchanger coefficients are tabulated in Table 3 for SSWEP #1 and SSWEP #2. For comparison, the superficial velocities, bed temperatures, total exchanger area, and bed depth are tabulated along with the "U" factors. In studying the data, it does not appear that any definite exchanger coefficient trends are evident within the framework of the test.

Weighted averages are calculated by multiplying the exchanger coefficients by their respective areas, summarizing the results, and dividing by the total area. Eliminating the high and low values, the average exchanger coefficient for the horizontal SSWEP exchanger tubes is 44.3 Btu/hr-ft^2-F.

For SSWEP #1, some auxiliary tube area was added so fluid-bed combustion at excess air levels between 20% and 50% could be observed. These tubes were added as vertical sections sandwiched between one of the outside horizontal tubes and the combustor wall. This abrupt change in tube orientation did not result in any significant change in exchanger coefficients.

Table 3

BED HEAT EXCHANGER OVERALL HEAT TRANSFER COEFFICIENTS, U (Btu/hr-ft^2-F)

SSWEP #1 Point	Superficial Velocity (ft/sec)	Factors: Horizontal Section 1+2	Horizontal Section 3	Horizontal Section 4	Vertical Section 5	Vertical Section 6	Weighted Average	Total HX Area (ft^2)	Bed Temp. (F)	Total Heat Transfer (Btu/hr)	Static Bed Depth (ft)
1	7.2	46.8	45.7	47.5	47.0	46.0	46.5	22.92	1325	1,130,000	2.6
2[a]	5.5	56.9	60.1	54.9	39.2	41.2	53.9	22.92	1247	1,230,000	2.5
3	6.1	42.2	45.5	off	42.8	44.7	43.4	18.39	1304	839,000	2.5
4	5.4	45.8	off		46.7	47.6	46.2	13.66	1294	635,000	2.6
5	5.4	43.8			43.5	42.6	43.6	13.66	1277	622,000	2.3
6	5.2	41.7			41.8	42.0	41.8	13.66	1193	551,000	2.3
SSWEP #2											
1	6.8	37.3	35.5	39.5	Not existent		37.3	18.52	1307	748,000	2.6
2	6.6	42.5	42.1	off			42.4	13.99	1392	708,000	3.3
3	5.0	41.9	40.5				41.4	13.99	1386	688,000	3.2
4	3.8	43.4	43.0				43.3	13.99	1368	747,000	3.7
5	4.1	47.3	off				47.3	9.26	1411	536,000	3.2

(a) Water-flow conditions not steady.

Exhaust Heat Exchanger Coefficients

Heat transfer coefficients at the different data points are tabulated in Table 4, along with the exhaust temperatures and calculated flow rates. For reference, the superficial velocities are also listed.

One should be careful in comparing the data. The drop in "U" factor is basically a result of blanking off available tube area with ash and elutriated media that settled in the exchanger body. In both SSWEP #1 and SSWEP #2, the cyclone rapidly plugged and filled with deposits to the point that it became merely part of the hot-gas ductwork. As a result, some ash and media leaving the combustor settled out in the exhaust exchanger and blanked off up to the lower third of the tube passes. This material, settling in the exhaust exchanger, was loose and free-flowing. Had the exchanger body been designed to draw off this material, no difficulty with any type of gravity-flow system would be expected.

Pneumatic Feed System

The original design conditions for the conveying air pipe were as follows:

- No more than 35% of the total airflow to the bed was allowed to be supplied by the fuel-line airflow. (Fuel-line air is part of the fluidizing air.)
- A theoretical fluidizing velocity of $2\frac{1}{2}$ fps at the bed bottom was required for full fluidization (not counting fuel-line air).
- MSW mass flow was required to be less than 300 $lb/min\text{-}ft^2$ in the 3-in. feed pipe.

The parameters listed above are based on previous CPC experience in burning MSW in a larger fluid bed than the CTU, and on knowledge of the fluidizing characteristics of the media used in the fluid bed.

The combustion air entering the bed as fuel transport air is a locally concentrated source of fluidizing air. If it exceeds 35% of the total air, the tendency for uneven fluidization and channeling of the air through the fluid bed increases. The percent feed-line air varied between 23% and 38%, as shown in Table 5.

The media used for fluid-bed operation is known to be quite well fluidized at a velocity of $2\frac{1}{2}$ fps. So long as this condition is maintained, fluidization below the feed port is assured. At less than $2\frac{1}{2}$ fps, the bed may or may not be adequately fluidized. SSWEP #2, points 3, 4, and 5, operated at velocities less than $2\frac{1}{2}$ fps below the feed point.

Table 4

EXHAUST HEAT EXCHANGER COEFFICIENTS, U

SSWEP #1 Point	Superficial Velocity (fps)	Exhaust Flow Rate[a] (lb/min)	Exhaust Exchanger Temp. In (F)	Exhaust Exchanger Temp. Out (F)	U Btu/hr-ft^2-F	ΔP (IWG)
1	7.2	79.1	1564	879	12.3	2.3[b]
2	5.9	69.0	1515	889	12.5	1.5[b]
3	6.1	69.3	1440	842	11.4	1.5
4	5.4	70.1	1425	882	12.2	2.5
5	5.4	75.3	1497	917	11.1	1.5
6	5.2	74.8	1282	828	10.1	1.9
SSWEP #2						
1	6.8	77.2	1500	891	13.3	1.8
2	6.6	69.4	1374	847	9.5	3.5
3	5.0	54.1	1398	818	8.7	3.0
4	3.8	41.8	1384	773	7.5	2.5
5	4.1	43.0	1237	722	6.5	2.0

(a) Calculated values.

(b) Estimated value due to senseline problem.

Table 5

SOLID-WASTE CONVEYING CHARACTERISTICS

SSWEP #1 Point	Total Combustion Air (SCFM)	Super-ficial Velocity (fps)	Combustion Pressure (IWG)	Feedrate Wet (lb/min)	Conveying Air (SCFM)	Conveying Air (fps)	Feedline Air (%)	Air Veloc. At Bed Bottom (fps)
1	928	7.2	10	12.0	217	70.5	23.0	4.3
2	794	5.9	12	12.0	208	67.7	26.0	3.2
3	806	6.1	11	12.0	217	71.2	26.0	3.4
4	784	5.4	52	13.5	254	75.8	32.0	2.7
5	863	5.4	95	12.5	320	89	37.0	2.6
6	863	5.2	92	12.0	320	89	37.0	2.5
SSWEP #2								
1	900	6.8	14	11.0	271.3	87.6	30.1	3.7
2	815	6.6	10	9.5	217	67.3	26.6	3.6
3	626	5.0	8	8.5	225.3	72.2	36.1	2.2
4	471	3.8	5	8.0	161.2	49.8	34.2	1.6
5	501	4.1	6	6.0	190.5	61.4	38.0	1.6

3.3 THREE-HUNDRED HOUR TEST

3.3.1 Test Summary

General

The 300-hour test (SSWEP #3) was conducted during the period August 18 through 31, 1979, in CPC's 7 ft^2 atmospheric fluid-bed combustion facility. A description of the equipment and test set-up was provided in Section 3.1. The objectives of this test were to:

- Demonstrate the feasibility of burning municipal solid waste in an atmospheric fluid-bed combustor with energy extraction from the bed.
- Evaluate the fluid-bed media and fluidization characteristics over a 300-hour period.
- Characterize exhaust-gas emissions.
- Measure bed heat transfer coefficients.
- Gather data on erosion and corrosion on typical boiler and superheater materials at representative tube wall temperatures.

Test Conditions

The planned test conditions, based on the results of SSWEP #1 and #2, were as follows:

Bed temperature	1400 F
Freeboard temperature	1600 F Max
Superficial velocity	4.5 ft/sec
Bed depth (slumped)	3.5 ft
Excess air	50-60%
In-bed tube heat transfer area	10.42 ft^2
Air-cooled corrosion specimens:	
Bed tube wall temperature	577 F
Freeboard tube wall temperature	800 F

Unprocessed MSW, obtained from the city of Palo Alto, California, was shredded and air-classified by CPC, with only the light fraction used as fuel. The average composition of the fuel is described in Appendices K and L.

The solids that were elutriated from the combustor and separated out in the cyclone were continuously reinjected into the fluid bed throughout the test.

Tube corrosion samples were installed in the fluid-bed portion of the combustor and in the freeboard gas path just above the combustor. These tubes were air-cooled to simulate fluid-bed boiler-tube wall temperatures.

Test Operations

The breakdown of the operational period is:

Total running time	310 hours
MSW combustion at planned test conditions	298 hours
Start-up time	11-1/2 hours
System downtime:	
Operator error at 24 hrs into test	10 minutes
Low water pressure in exhaust-gas cooling system at 82 hrs into test	19 minutes

The test was completed without any significant combustion-related problems, and the operating conditions remained substantially constant throughout the test. The only upsets in addition to the downtime shown above were caused by feedline plugs which occurred 35 times during the test. These blockages were caused most frequently by large plastic lids which did not shred during fuel preparation. However, the blockages were cleared within 3 to 5 minutes, while combustor operation was maintained on oil.

The in-bed air-cooled tube failed after 135 hours due to a mechanical failure unrelated to corrosion.

Test Results (Typical)

Detailed data for the entire test is provided in Section 3.3.2.

Data from the twelfth day of operation (259 through 266 hours into the test) have been included in this section as representative of general test conditions and results.

Note that sample time periods for emissions and gas analysis are identified and that, during two hours of that period, gas analysis data were being recorded by the California Air Resources Board (CARB) using their mobile equipment.

Test Conditions. The comparison of actual versus planned test conditions during the time CARB was monitoring the flu-gas composition is shown as follows:

Parameter	Planned	Actual
Bed temperature	1400 F	1383 F-1393 F
Freeboard temperature	1600 F max	1478 F-1520 F
Superficial velocity	4.5 ft/sec	4.6 ft/sec
Excess air	50-60%	47% average

Exhaust Gas Emissions. The comparison of gas-analysis data recorded by CPC and CARB is shown below.

	CPC	CARB
O_2	7.0%	6.7%
CO_2	13.5%	13.3%
CO	200 ppm	250 ppm
SO_2	20 ppm	55 ppm
NO_x	220 ppm	180 ppm
(Hydrocarbons as CH_4)	23 ppm	6 ppm
HCl	90-190 ppm	---

Particulates. A total of 19 particle-loading samples were taken during the entire test, using both Andersen Cascade Impactors and EPA Method 5. The results are shown below:

Location	gr/acf Range	gr/scf Range
Cyclone inlet	20-60	80-240
Cyclone outlet	2-4	7-14
Baghouse outlet	.02-.07	.03-.12

Based on these data, 10-20 lbs/minute of solids were being reinjected to the bed.

Tube Heat Transfer Coefficients. The overall heat transfer coefficients increased during the 300-hour test. This increase was rapid during the first day, then much more gradual. During the last six days of testing, very little, if any, increase could be detected. The section on Bed Heat Exchangers (page 24) presents more detailed data on the exchanger coefficient and links their increase to a decreasing bed-particle size. Over the last six days of testing, the overall heat transfer coefficient (weighted area average) was 60.3 Btu/hr-ft^2-F.

Combustion Efficiency. Using the calculation techniques shown on page 24, combustion efficiency was computed using the average values of CH_x, CO, and C. The results showed that a 99.0% combustion efficiency was obtained over the test duration. Computation of the minimum and maximum efficiency yielded 98.6% and 99.3%, respectively.

Corrosion Samples. The freeboard samples (an air-cooled tube) were installed horizontally in the ductwork connecting the CTU combustor and the recycle cyclone. They were exposed to 1500 F - 1600 F combustor flue gases heavily laden with particulate (40-50 gr/acf) at a velocity of about 35 fps. The sample tube wall temperature was about 720 F. As a result, a combination of corrosion and erosion resulted in significant metal wastage on the carbon steel specimens, with less wastage apparent as the alloy content increased.

Corrosion and scale were measured on all samples. The results are summarized below:

a. Austenitic Steels

- 18Cr-8Ni (SA-312-TP304H)
- 16Cr-12Ni-2Mo (SA-312-TP316H)
- Incoloy 825 (Ni-Fe-Cr-Mo-Cu)

These steels showed the best erosion-corrosion resistance, although erosion-corrosion rates were still unacceptably high. Obviously the abrasion problem on the gas-facing side must be dealt with by lowering particulate concentrations, lowering gas velocities, or by incorporating abrasion shields. Scaling was about the same for the 304 S.S. and 316 S.S., both being slightly scaled. The Incoloy 825 showed no evidence of scaling except on the gas-facing side. The only concern with this class of alloys was the moderate corrosion penetration on the Incoloy 825.

b. Low-Alloy Steels

- 1-1/2 Cr - $\frac{1}{2}$ Mo-Si (SA-335P11)
- 2-1/2 Cr - 1 Mo (SA-335P22)

The low-alloy steels showed little corrosion penetration, but were noticeably scaled and spalled. In addition, the erosion-corrosion attack on the gas-facing side was higher than for the austenitic steels.

c. Carbon Steel

- SA-106 B

Plain carbon steel showed high metal wastage due to erosion-corrosion, and there was significant scaling and corrosion penetration.

3.3.2 Analysis of Test Results

Process Conditions

Process Temperatures. Figure 10 shows the fluid-bed and freeboard temperatures as a function of time. Data points are plotted every three hours. The downward spikes in bed temperature occurred when feedline plugs temporarily halted fuel flow. The average bed temperature for the entire 300-hour test was 1391° F, with a range of 1307 to 1425° F. This compares favorably with the target bed temperature of 1400° F. The freeboard bed temperature plotted in Fig. 10 is shown to oscillate significantly during the test, although there is a downward trend throughout the first half. Freeboard temperatures are shown never to exceed the 1600° F maximum designated as a test condition.

It is apparent that this 300-hour solid-waste combustion test operated completely free of the deposit problems that occurred in the two 50-hour test

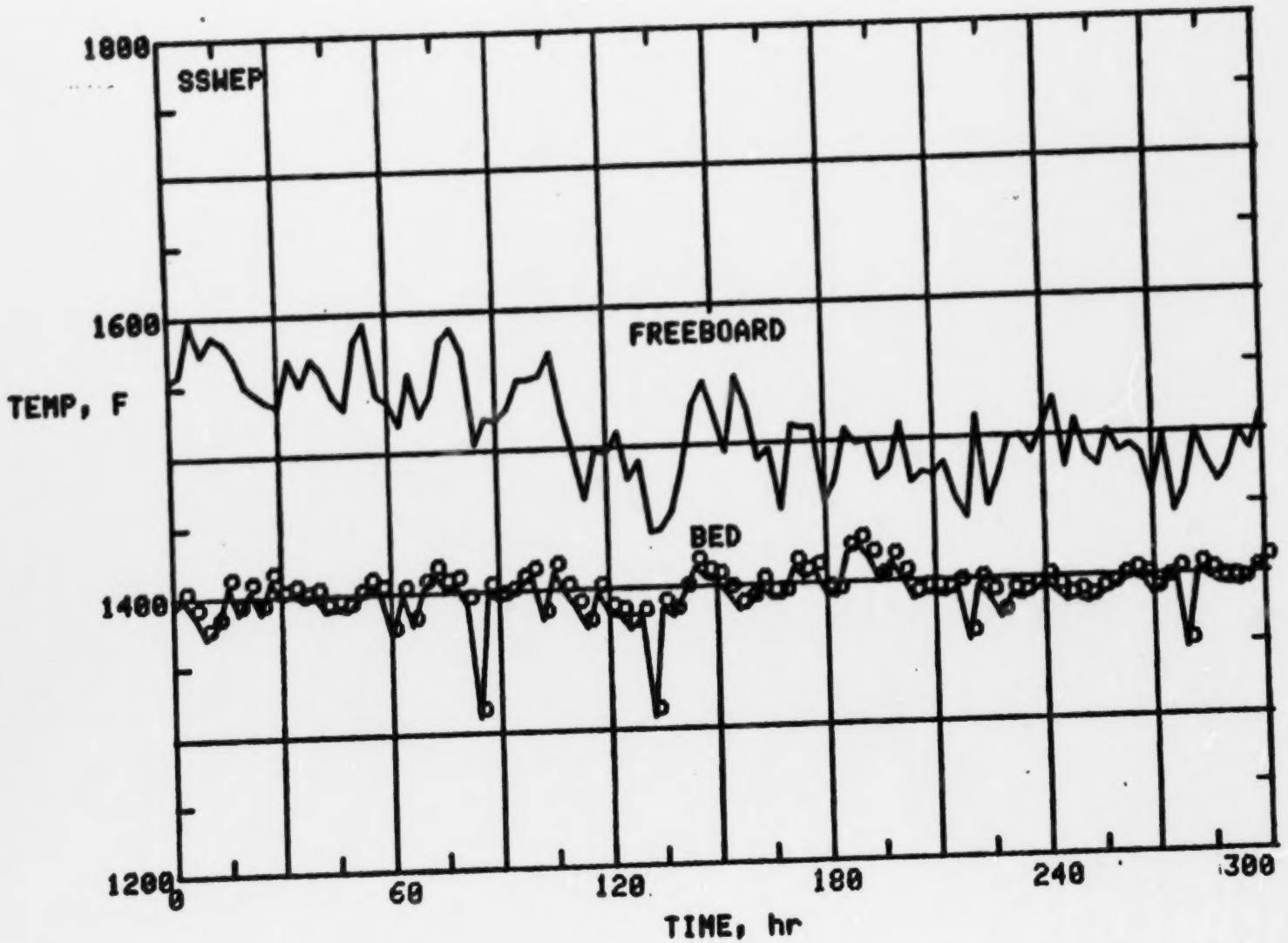

Figure 10. Freeboard and bed temperature, 300 hour test.

runs. It was theorized, following those earlier tests, that temperatures below 1600° F in the freeboard would be required to prevent deposit formation. The plot in Fig. 10 supports this theory.

Superficial Velocity. Figure 11 shows the variation in superficial velocity as a function of time.

Superficial velocity is defined as the air flow through an empty combustor at the average bed temperature and freeboard pressure. Air flow consists of the solid waste conveying air plus the air entering through the distributor plate.

Through the first 105 hours, superficial velocity averaged 4.4 ft/sec. Upward spikes at hours 63 and 87 were from short-term increases in air flow. After test hour 105, the air flow was purposely raised to increase excess air, which had been averaging less than 40% for the previous 15 hours. Superficial velocity averaged about 4.6 ft/sec for the remainder of the test. This was acceptably close to the target value for superficial velocity of 4.5 ft/sec.

Excess Air. Figure 12 shows the excess air plotted as a function of time. The breaks in the graph indicate times when the excess air level was not known with reasonable certainty. Target value for excess air was 50-60%. During the first 100 hours of testing, the excess air dropped slowly from about 50% to less than 40%. As discussed above, a decision was made at that time to increase air flow to increase excess air. After the first 100 hours, the excess air was recorded generally above 40%. The average excess air for the last 144 hours (6 days) was 44%.

Excess air averaged below the targeted range because the heat transfer coefficient to the bed tubes rose to about 60 Btu/hr-ft^2-F, whereas it was estimated at 45 Btu/hr-ft^2-F based on SSWEP #1 and SSWEP #2. This phenomenon, discussed in more detail in the next section, resulted in more heat being removed from the bed than was anticipated. Consequently, the balance point on the process conditions of temperature, superficial velocity, and excess air was shifted. A decision was made to accept the lower excess air and to keep temperatures and superficial velocity close to target values. To have raised excess air, superficial velocity would have had to be increased.

The 300-hour test demonstrates that the process conditions listed below are within the feasible operating range:

Bed temperature	1307-1425 F
Freeboard temperature	1443-1596 F
Superficial velocity	4.4-4.6 ft/sec
Excess air	40-50%

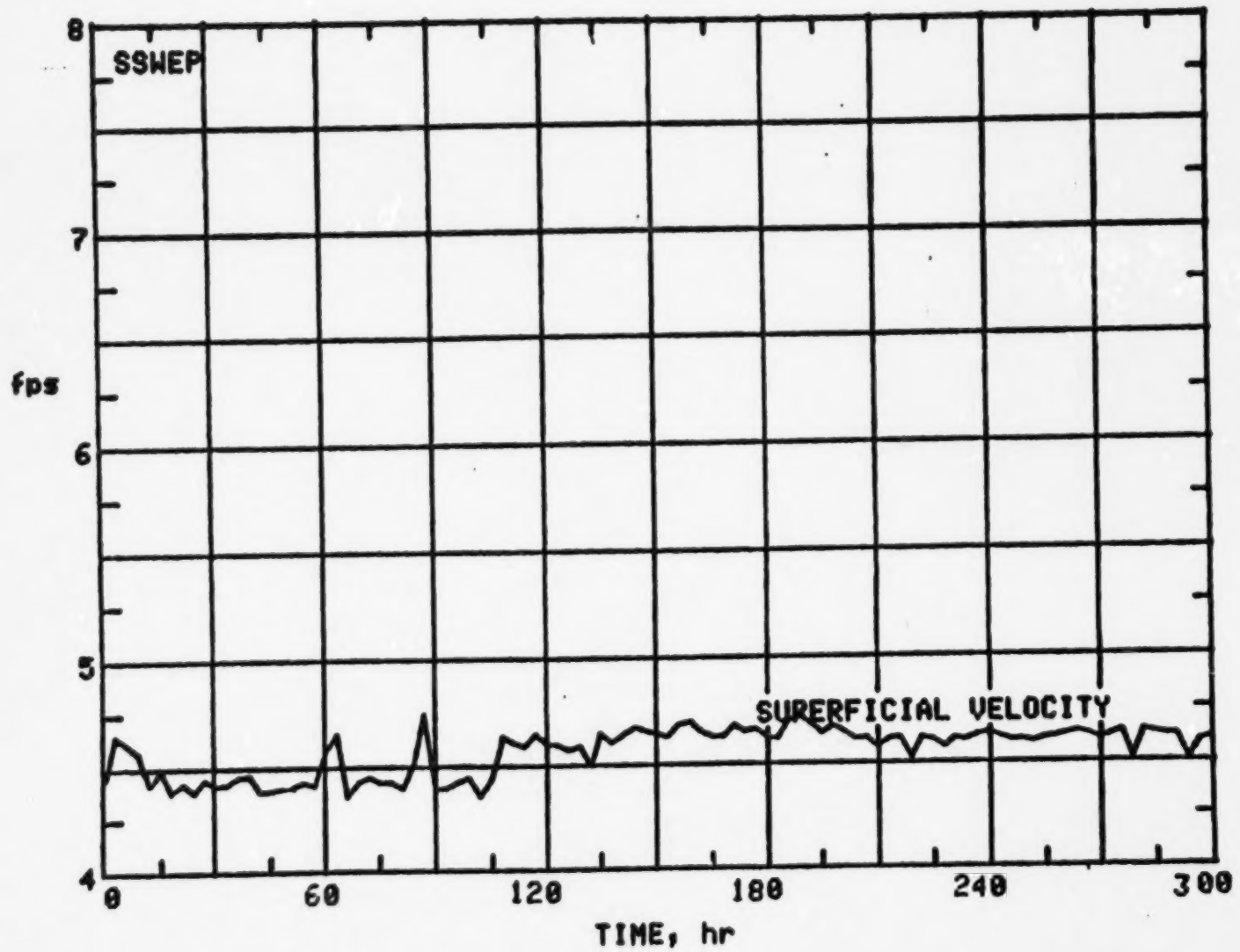

Figure 11. Superficial velocity, 300 hour test.

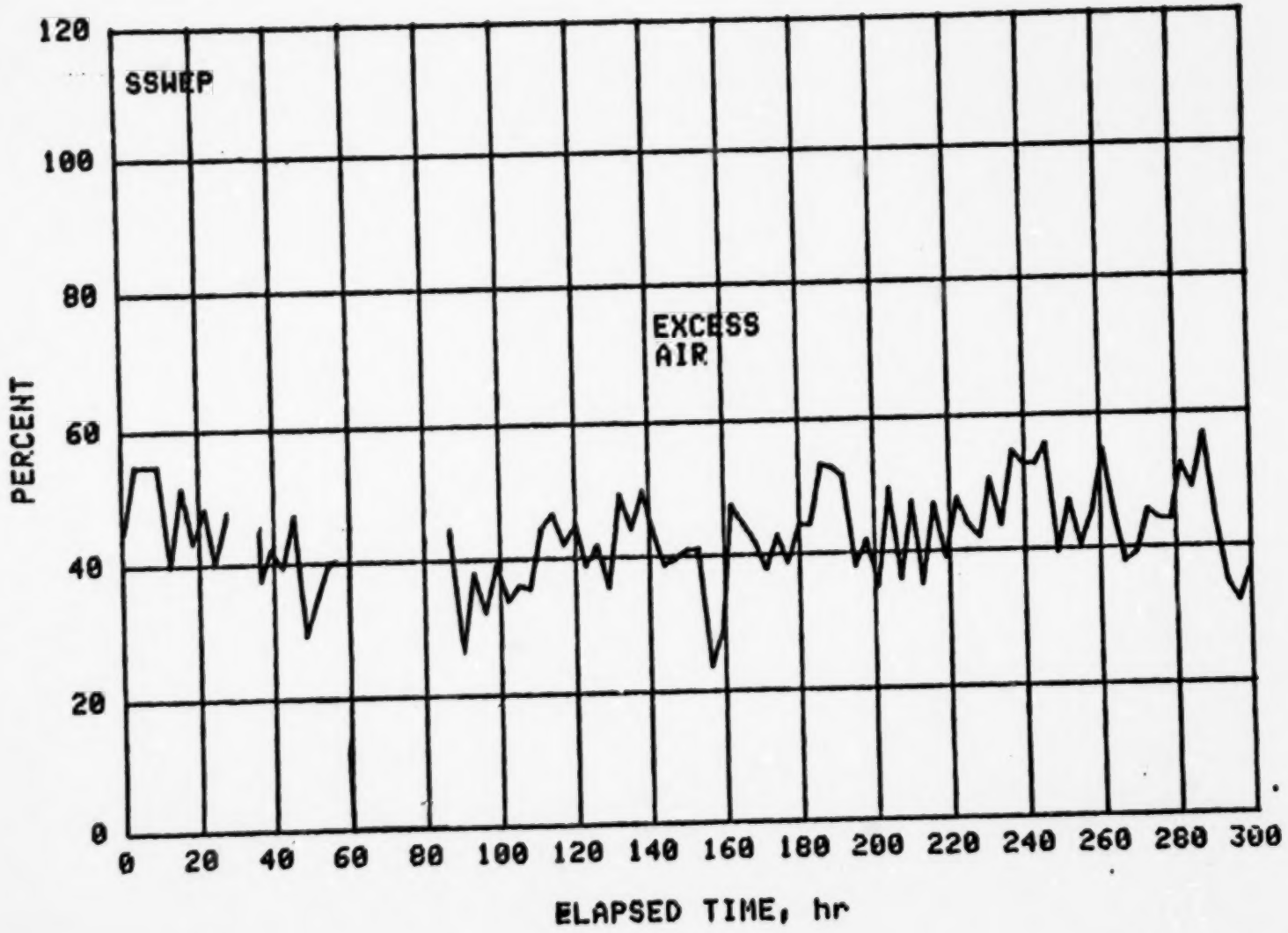

Figure 12. Excess air, 300 hour test.

Bed Heat Exchangers

Figure 13 is a graph of the overall heat transfer coefficients in Btu/hr-ft^2-F as a function of time.

Heat exchanger No. 1 is a small, two-pass coil arranged vertically in the bed. Its location is shown schematically in Fig. 3. Exchanger No. 1 has a heat transfer area of 0.96 ft^2. Figure 13 shows the heat transfer coefficient for exchanger No. 1 in the 45-50 Btu/hr-ft^2-F range early in the test, but rapidly climbing to 80-90 Btu/hr-ft^{2}F. This increase and the resulting high value in the heat transfer coefficient may be attributed to the following observations:

1. Exchanger No. 1 is quite small in relation to the bed and the other exchanger bundles. This exchanger type has been used in other tests, with other fuels, and has typically shown higher heat transfer coefficients and more sensitivity to bed changes than other tube configurations.

2. As the average bed particle size decreases, the heat transfer coefficient increases.[1] With the decrease in average bed particle size described in the section on Fluid Bed, Recycle, and Baghouse Material (p. 46), an increase in outside heat transfer coefficient of 40-50% would be predicted by Bashakov or Locke.[2] The overall heat-transfer coefficient actually increased about 70% on the short two-pass tube. For the configuration used, the outside coefficient and overall coefficient are close to equal.

3. Note in Fig. 3 that the short, two-pass tube was installed opposite the pneumatic feed-pipe exit. Localized, increased bed activity may have occured near this tube to increase the exchanger coefficient.

Heat Exchanger No. 2 consisted of two four-pass, horizontal tubes arranged in the bed as shown in Fig. 3. The exchanger area was 9.46 sq ft. The plot of the Exchanger No. 2 coefficient, Fig. 21, has the same shape as the plot for Exchanger No. 1, although the increase is less pronounced. Early in the test, the heat transfer coefficient averaged 46 Btu/hr-ft^2-F. By the end of the test, the heat transfer coefficient became fairly stable at 58 Btu/hr-ft^2-F, for a 26% increase. The decrease in bed media size would cause the increase in the heat transfer coefficient in Exchanger No. 2 for the following reasons.

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[1] Bashakov et al., Powder Technology, 1973, pp. 8, 273.

[2] Locke, H. B., et al., "Fluidized Combustion in Great Britain," presented at Fourth International Conference on Fluidized Bed Combustion, Mitre Corporation, McLean Virginia, December, 1975.

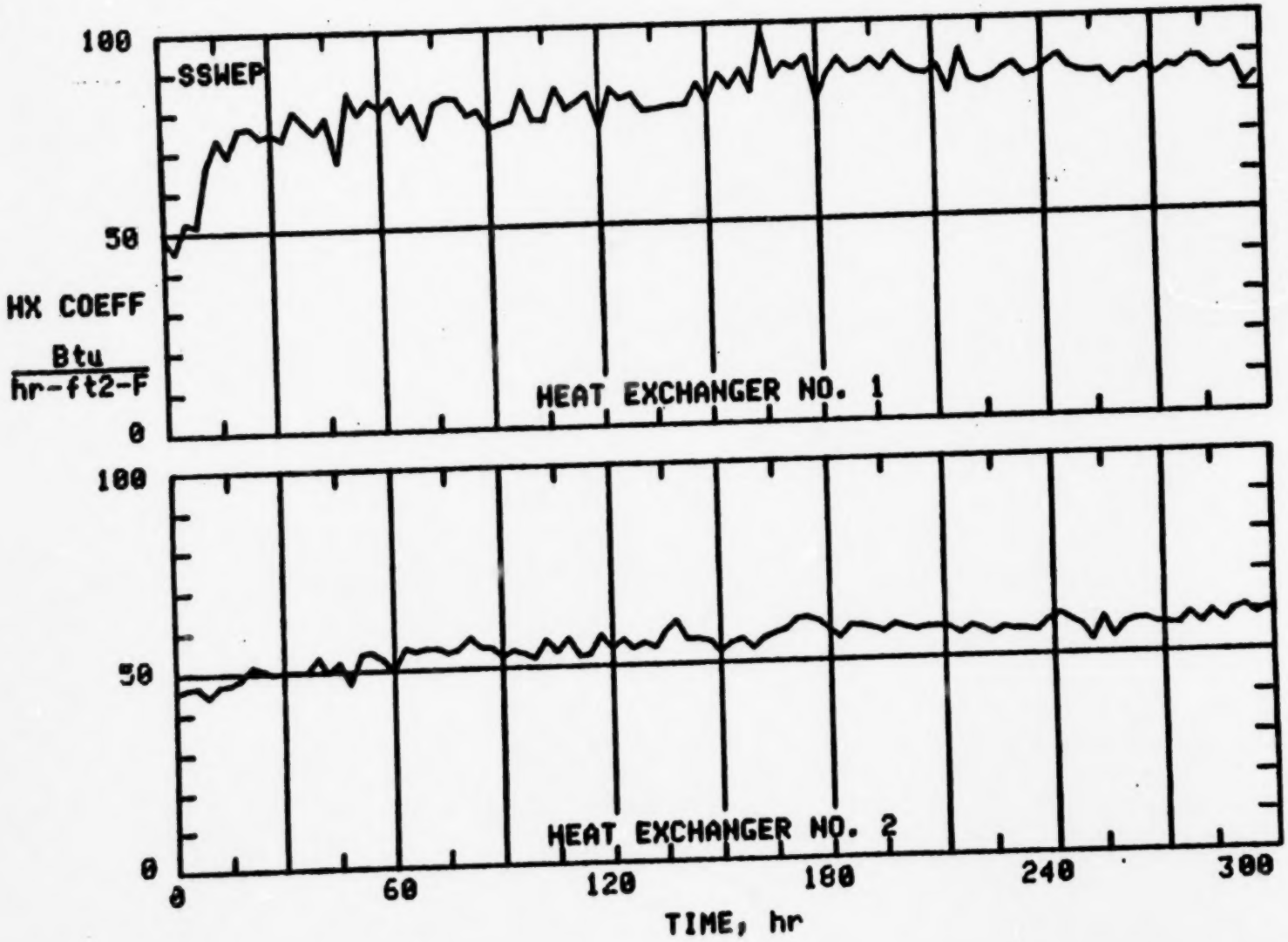

Figure 13. Heat transfer coefficients for in-bed exchangers, 300 hour test.

1. Exchanger No. 2 is fairly large in relation to the bed and Exchanger No. 1. The heat transfer area is 9.46 ft^2 versus .96 ft^2.

2. Exchanger No. 2 occupies regions high and low in the bed and in all four quadrants on a plan view. Any local variations in heat transfer rate would be balanced over the entire area.

Flue-Gas Composition

Flue-gas composition was monitored continuously throughout the 300-hour test. These data were supplemented by Orsat-sampling at four-hour intervals for much of the test. The gas-composition data are portrayed graphically in the following figures:

Figure 14	Oxygen and carbon dioxide (O_2 and CO_2)
Figure 15	Carbon monoxide (CO)
Figure 16	Hydrocarbons (CH_4)
Figure 17	Sulfur dioxide (SO_2)
Figure 18	Nitrogen oxides (NO_x)

Gas data were unavailable for short periods over the first 100 hours (four days) of testing. This was due to the high levels of dust in the flue gas plugging the filters in the sample lines. Suitable maintenance techniques developed by the fourth day of operation solved this problem, and consistent gas data were generally available over the last 200 hours of testing. On the 12th day of operation, the California Air Resources Board portable equipment was on line to verify gas data. Comparative results for this day are presented in the section on Exhaust Gas Emissions (p. 31).

Figure 14 shows the O_2 and CO_2 varying quite significantly during the 300-hour test. For example, during the last 144 hours (six days), the O_2 varied between 4.6% and 8.5% and averaged 6.7%. This reflects the constantly changing characteristics of the fuel and a varying fuel-feed rate. The excess air plotted in Fig. 12 is calculated based on the O_2 and CO_2 concentrations. In fact, the general trend and shape of the O_2 curve matches the excess air curve.

The CO and hydrocarbons (shown as CH_4) would constantly vary and sometimes spike quite high, as shown in Figs. 15 and 16. Once again, fuel composition and feed rate oscillations probably account for this observation. Note, also, that CH_4 was not recorded until the 114th test hour.

SO_2 levels, plotted in Fig. 17, generally remained very low. The average of 30 ppm over the last 144 hours amounts to about .06 lb/million Btu input. Occasionally SO_2 would jump to uncharacteristically high levels. The SO_2 reached 100 ppm at the 150th test hour and 200 ppm at the 300th test hour. This would be caused by occasional injection of large pieces of sulfur-containing waste.

The most representative NO_x data were gathered during the last 180 hours of the test and are plotted in Fig. 18. For reference, all the NO_x data are tabulated in Appendix G. During the last 144 hours, the NO_x

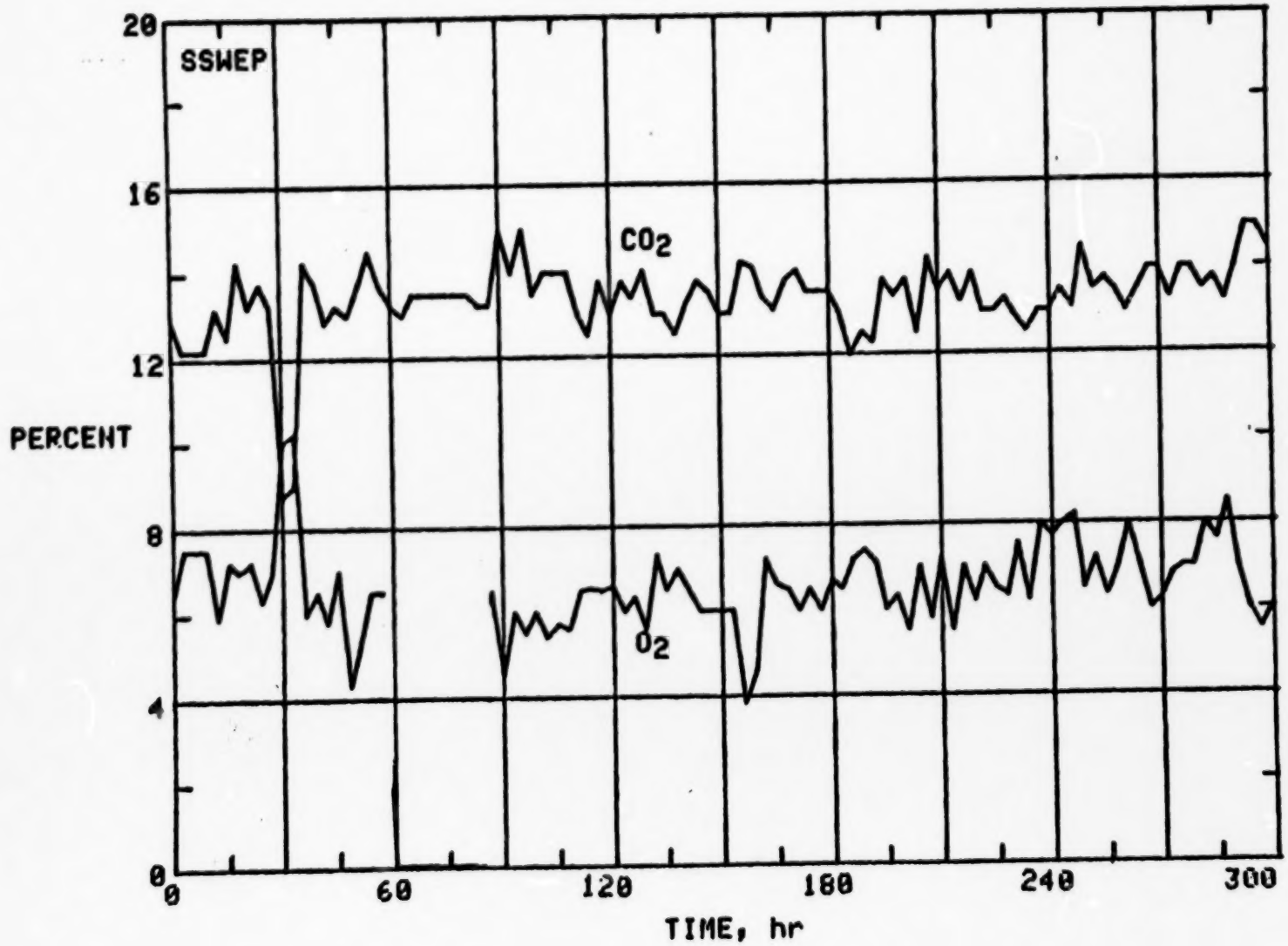

Figure 14. CO_2 and O_2 readings, 300 hour test.

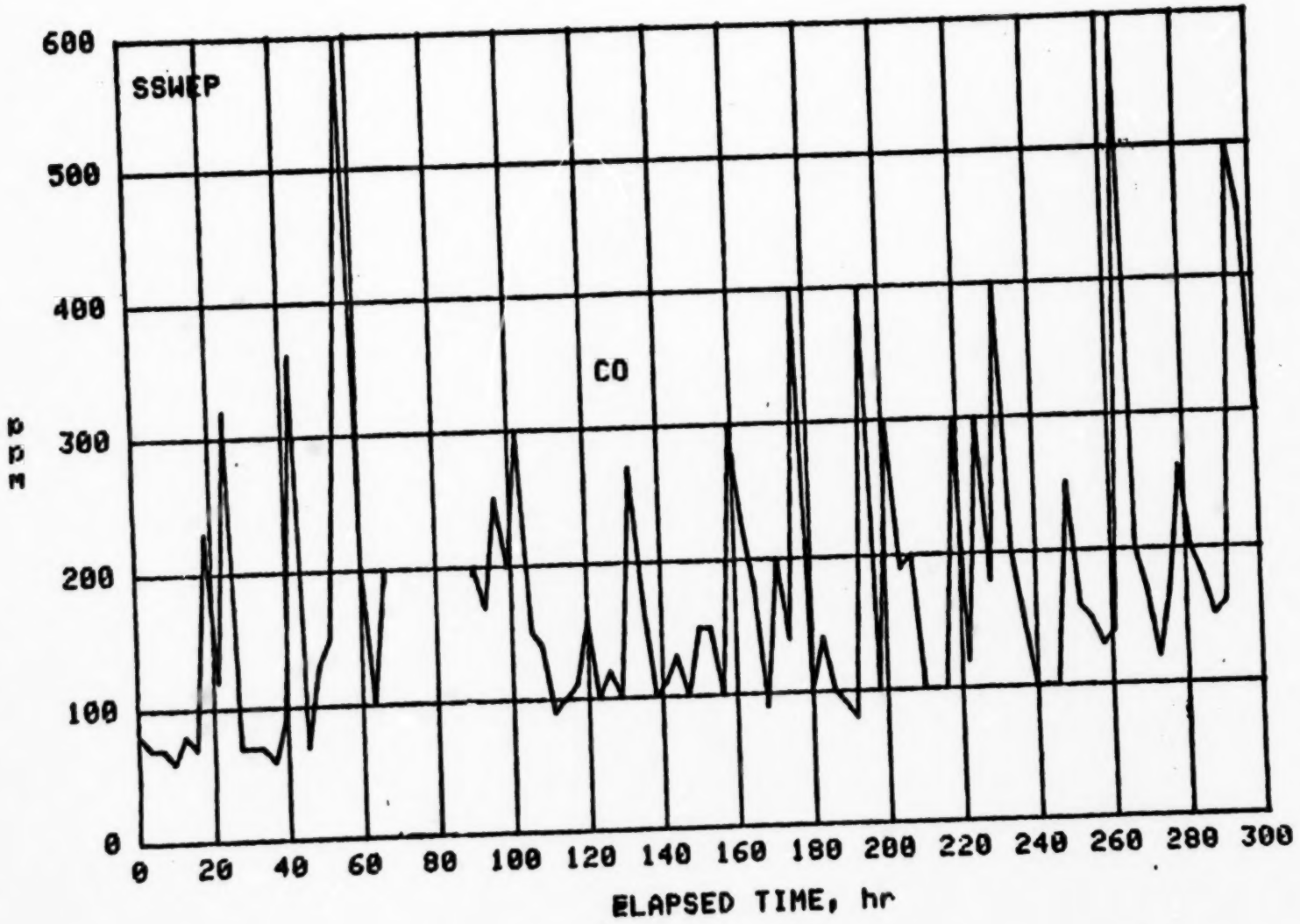

Figure 15. CO readings, 300 hour test.

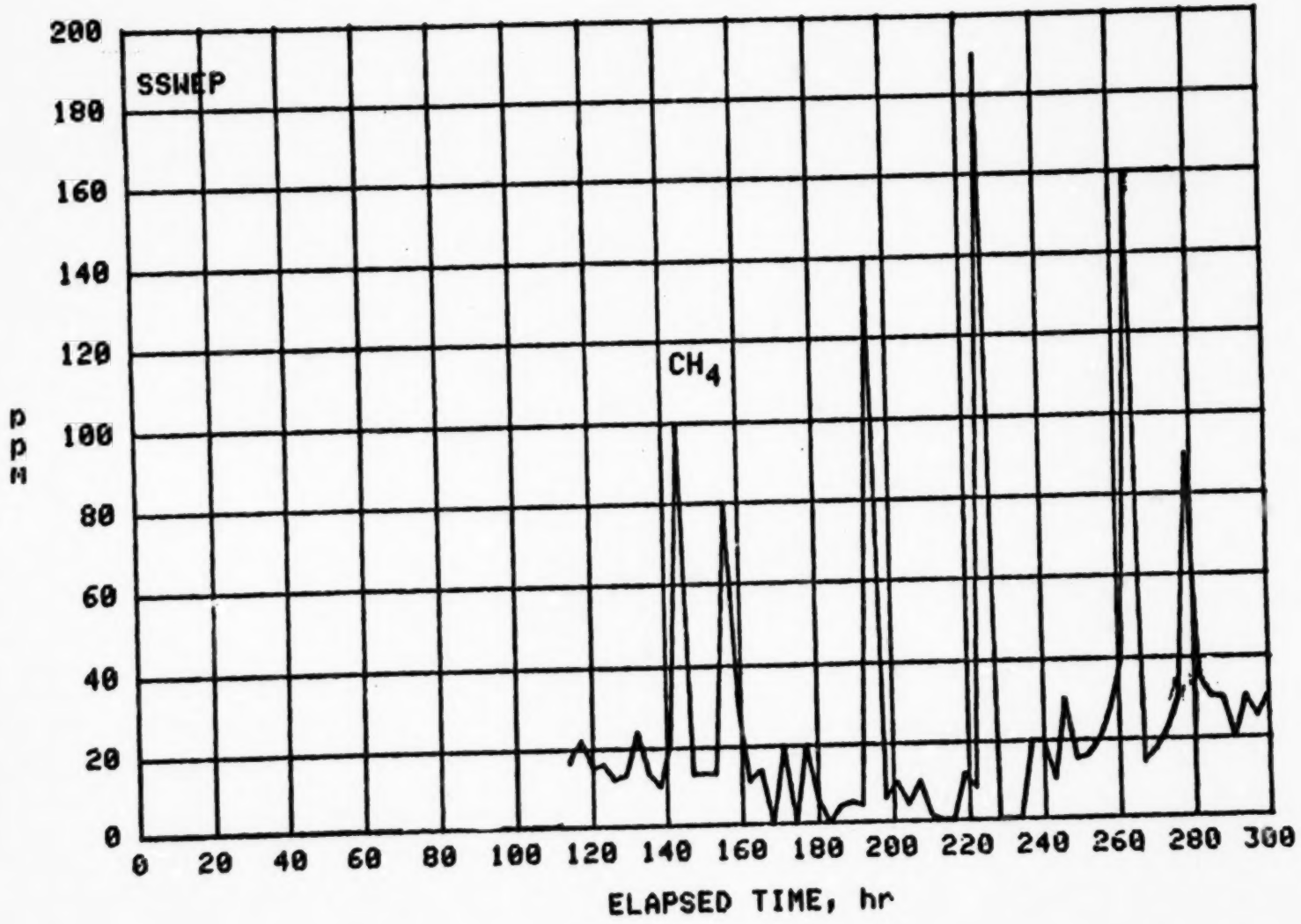

Figure 16. Unburned hydrocarbon readings, 300 hour test.

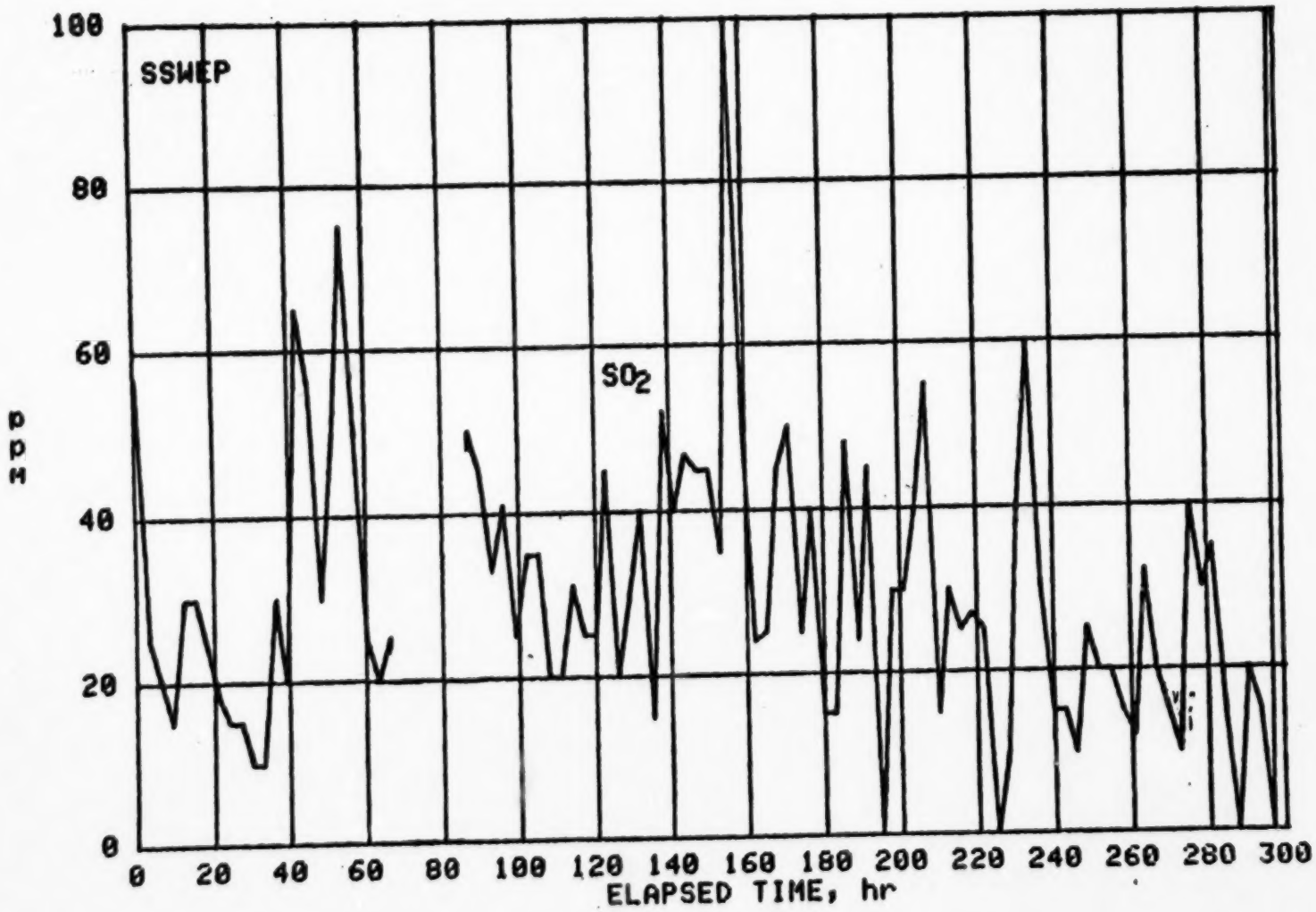

Figure 17. SO_2 readings, 300 hour test.

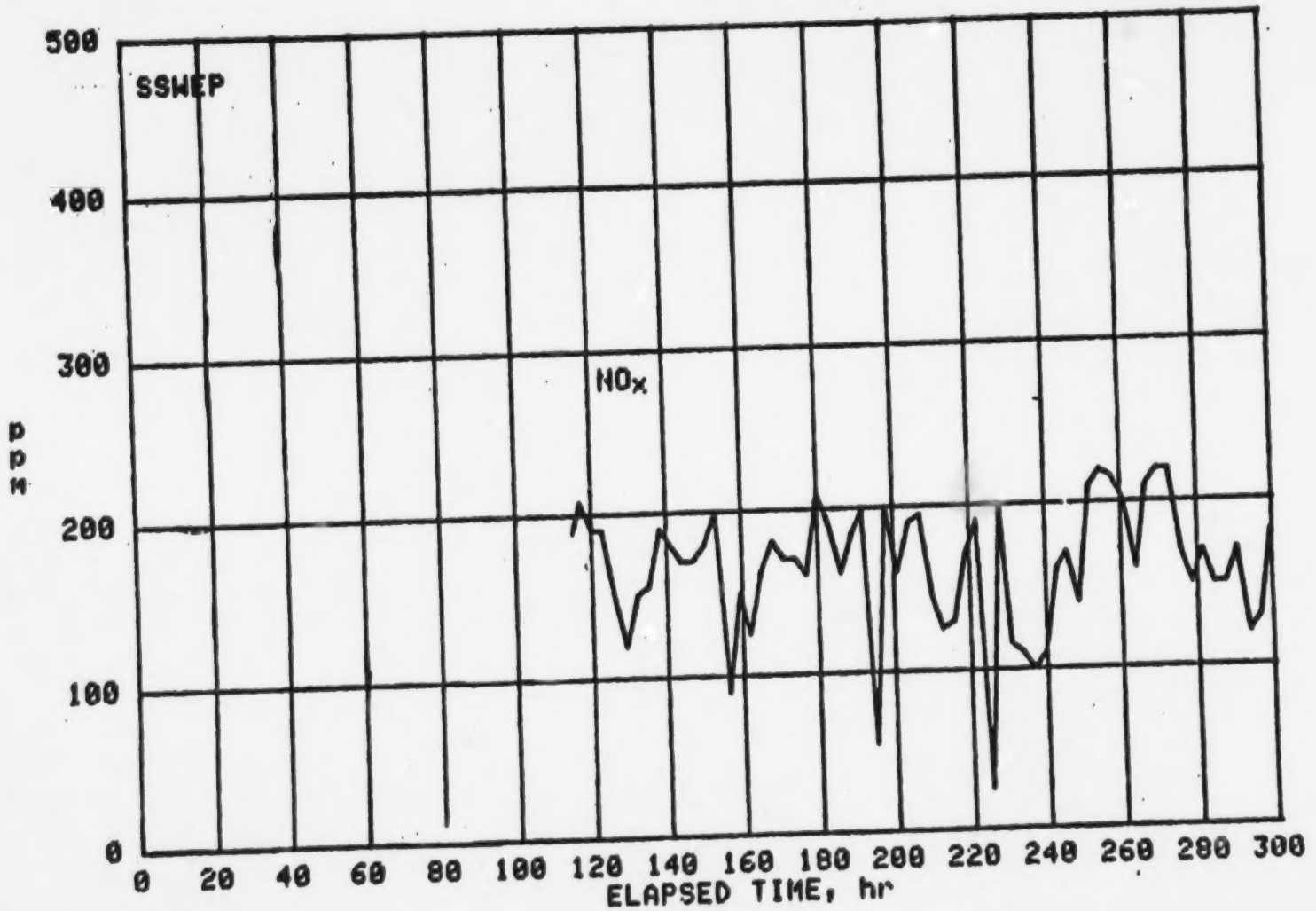

Figure 18. NO_x readings, 300 hour test.

averaged about 160 ppm and generally ranged between 100 and 200 ppm. 160 ppm translates to about .25 lb/million Btu input.

Fuel Composition

Daily samples of the processed MSW fuel were analyzed both by CPC and Commercial Testing and Engineering Company.

CPC analyzed the fuel samples for moisture and obtained an average of 26.3%. Commercial Testing and Engineering performed proximate and ultimate analysis on the fuel. Their results are averaged below:

Proximate Analysis

(as received)

	Average	Range
Moisture fraction (%)	23.6	17 - 26
Ash fraction (%)	10.6	9 - 13
Volatiles (%)	57.6	54 - 64
Fixed carbon (%)	8.2	8 - 9.7
Higher heating value (Btu/lb)	5572	5250 - 6050

Ultimate Analysis

(dry weight %)

Carbon	44.46	43.9 - 45.2
Hydrogen	5.96	5.8 - 6.1
Oxygen	34.32	32.2 - 35.6
Nitrogen	0.67	.63 - .80
Chlorine	0.49	.40 - .67
Sulfur	0.13	.09 - .17
Ash	13.97	12.0 - 16.0
Higher heating value (Btu/lb)	7352	6900 - 7700

The ash derived from two fuel samples was analyzed for mineral content. Results are shown in Appendix M. As expected, the major components were Si, Al, Ca, and Fe. In addition, significant but not excessive alkali (Na and K) content was found.

Particulate and HCl Sampling

The fluid-bed combustor flue gas was sampled for particulate loading and size distribution upstream and downstream from the recycle cyclone. These locations are shown schematically in Fig. 2. HCl concentration of the flue

gas was also measured daily, using the proposed EPA procedures described in "HCl Concentrations in the Flue Gas," below.

Particulate-Sampling Results. Particulate-loading data are displayed graphically in Figs. 19 and 20 for the cyclone inlet and cyclone outlet, respectively. The loadings in both locations were very high. As a result, short sampling times were necessary to avoid plugging or overloading the sampling probes. Sampling times were typically:

Cyclone inlet	6 minutes
Cyclone outlet	16 and 20 minutes
Baghouse outlet	60 minutes

At the cyclone inlet, the particulate loading varied from 90 to 290 gr/sdcf, with no noticeable trend over the 300-hour test. The average loading was 170 gr/sdcf.

At the cyclone outlet, the particulate loading varied between 8 and 14 gr/sdcf over the last 225 hours of testing and averaged 10 gr/sdcf. The outlet loading trend was fairly flat, indicating an equilibrium level had been reached.

Data obtained from the Andersen Impactor can be reduced two ways. First, because the impactor collects all particulate, and the connected sample train maintains isokinetic conditions and measures gas flow, a total particulate loading is available as with the EPA-5 sampling. Second, the Andersen Impactor separates the solids by size, so a distribution can be determined. During the solid-waste combustion test, the Andersen Impactor was affected by two operational problems. First, the impactor plates were overloaded on all samples. Second, water condensation was discovered in the impactor plates, which can cause the plates to plug. These two circumstances invalidated the data used in determining particle-size distribution, but did not invalidate the data needed to determine particle loadings.

HCl Concentrations in the Flue Gas. Exhaust-gas samples were taken daily for measurement of HCl, and the concentration was determined following proposed EPA procedures, summarized as follows. The HCl-containing gas was trapped in impingers containing 0.1 N NaOH; the impinger contents were then titrated to determine actual chloride concentration. All chloride trapped by the impinger was considered to come from captured HCl gas. Particulates were filtered from the sample gas before impingement. The variation in HCl concentration throughout the test is plotted in Fig. 21. The average concentration of chloride as HCl in the gas was 0.07 gr/sdcf, or 100 ppm (volume basis).

Fluid Bed, Recycle, and Baghouse Materials

Fluid Bed Material. The original bed material was Monterey 16-mesh sand. Typical sieve analysis of this material yields an average particle size between 1.0 and 1.1 mm. The sample of Monterey 16 mesh sand taken on 8/18/79, constituting the first bed sample, produced an average particle size of 1.053 mm. Figure 22 shows the average particle size of the bed as a

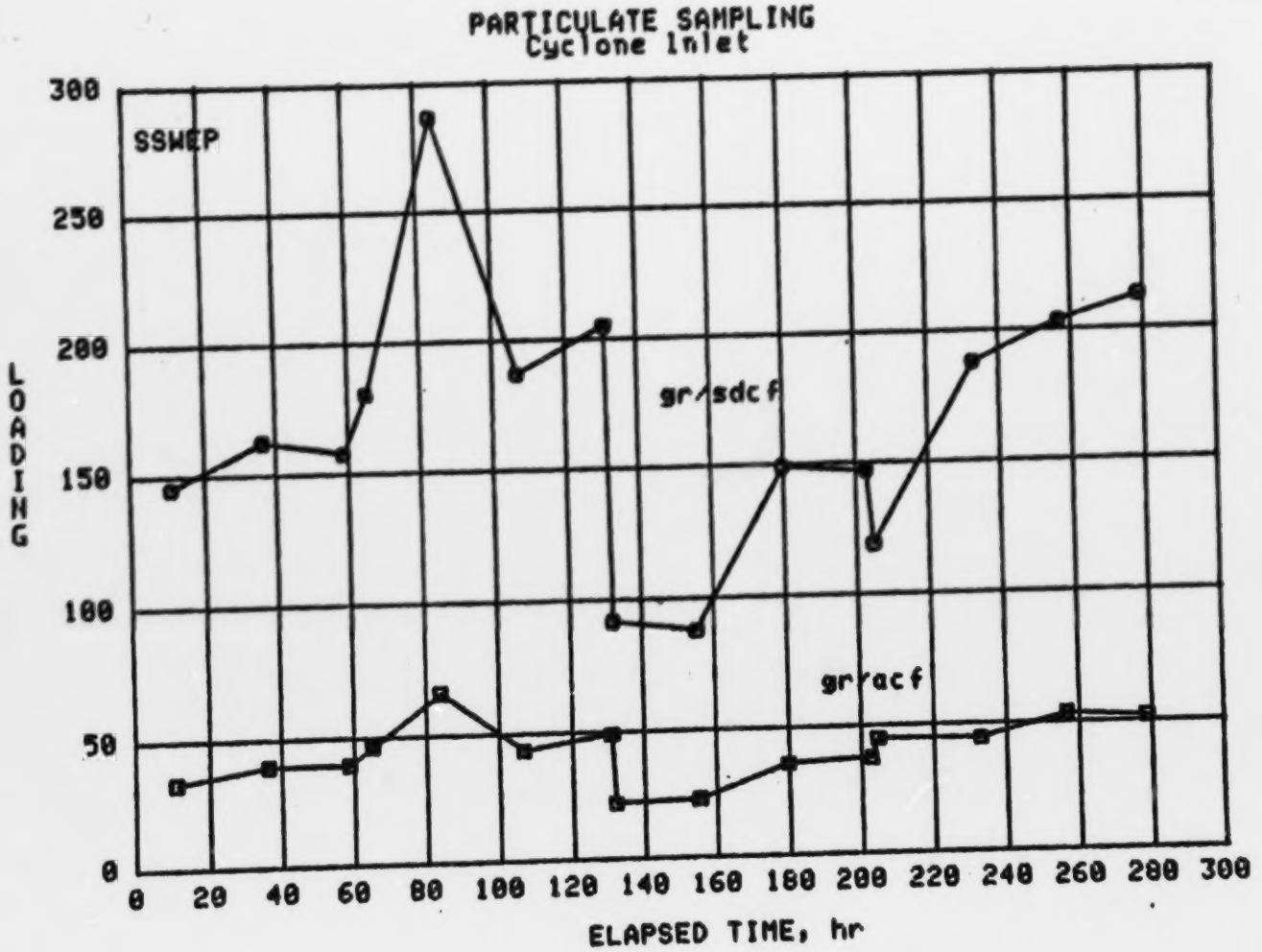

Figure 19. Particulate loading at cyclone inlet, 300 hour test.

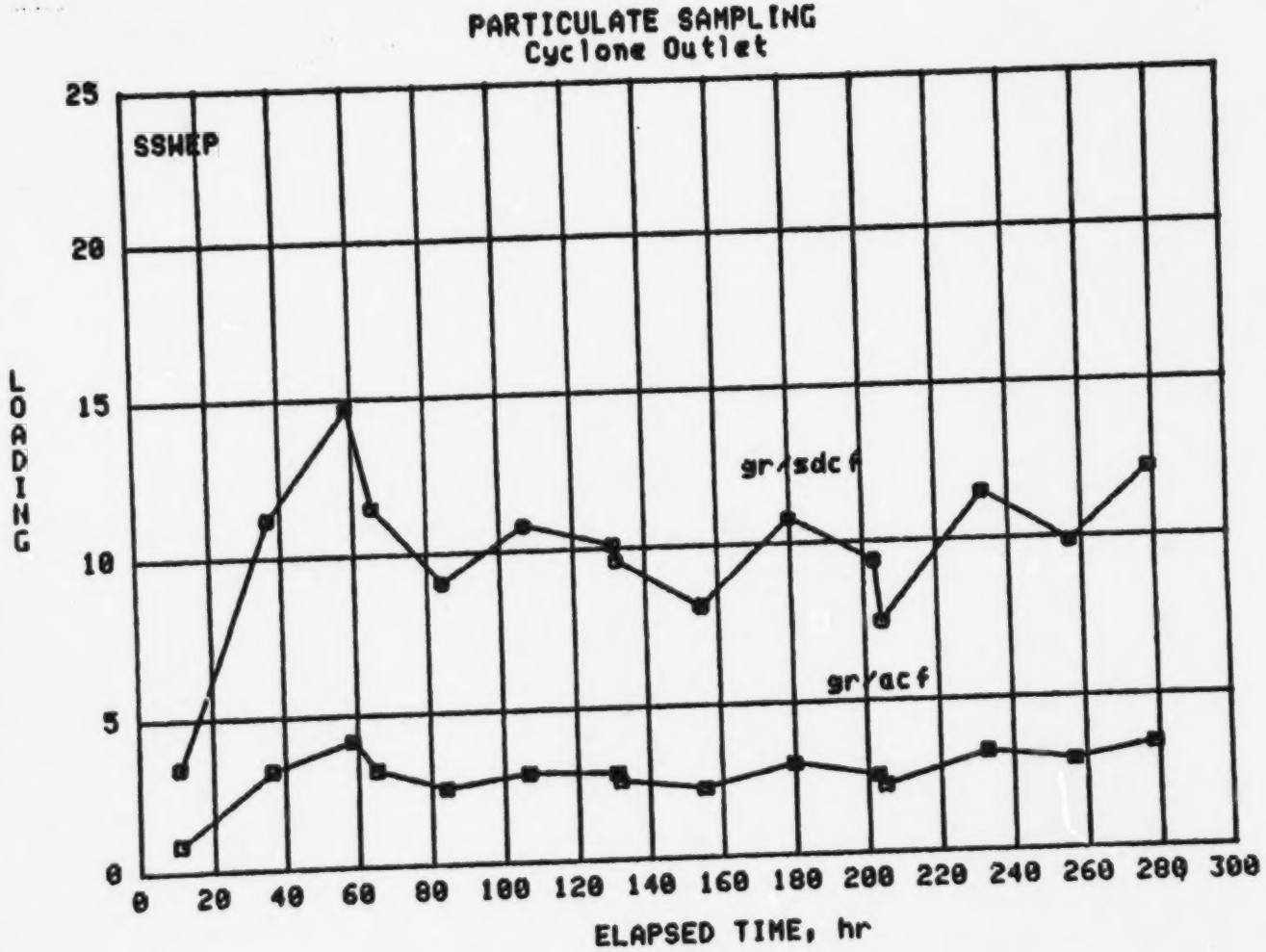

Figure 10. Particulate loading at cyclone outlet, 300 hour test.

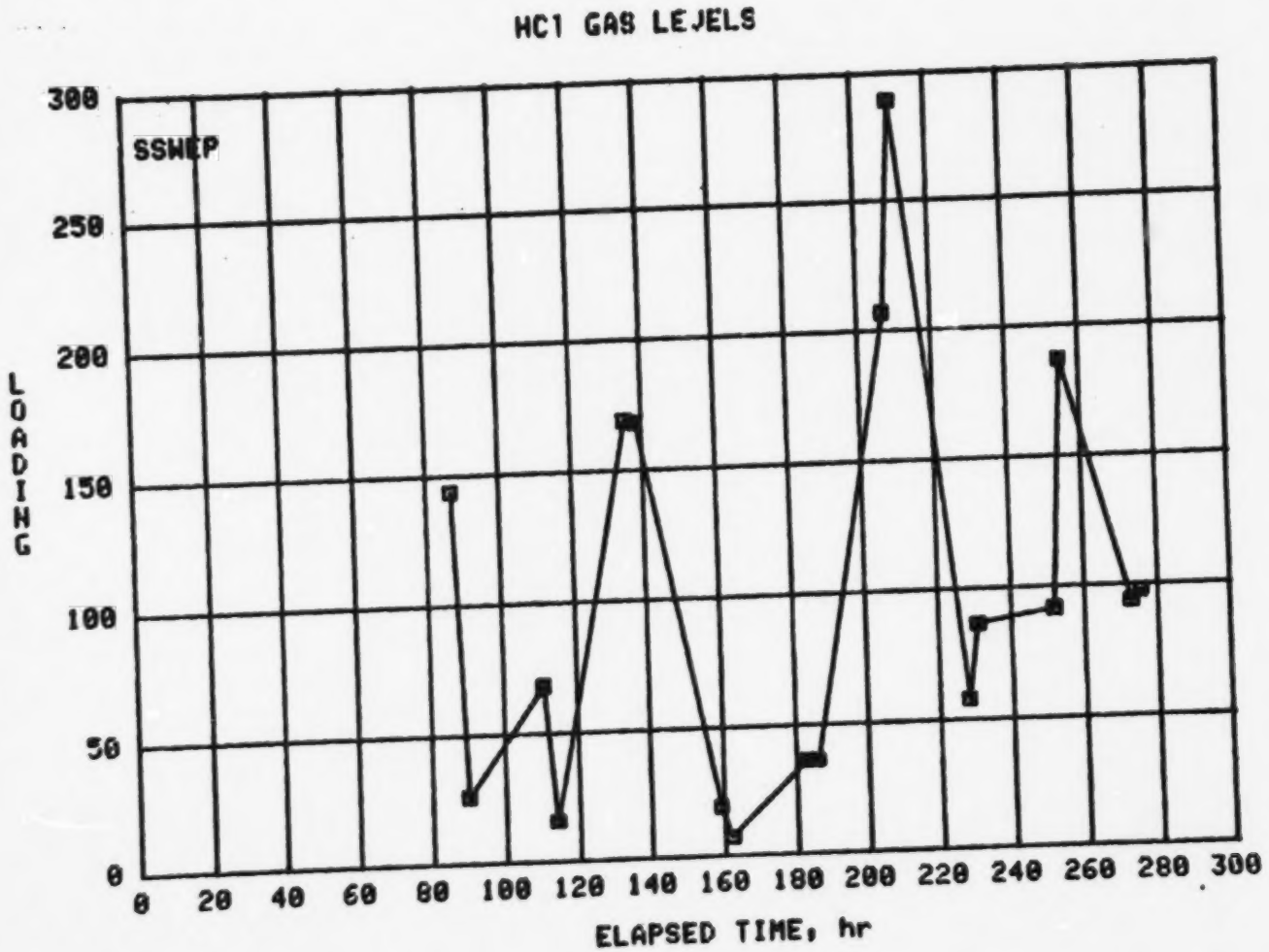

Figure 21. HC1 measurement, 300 hour test.

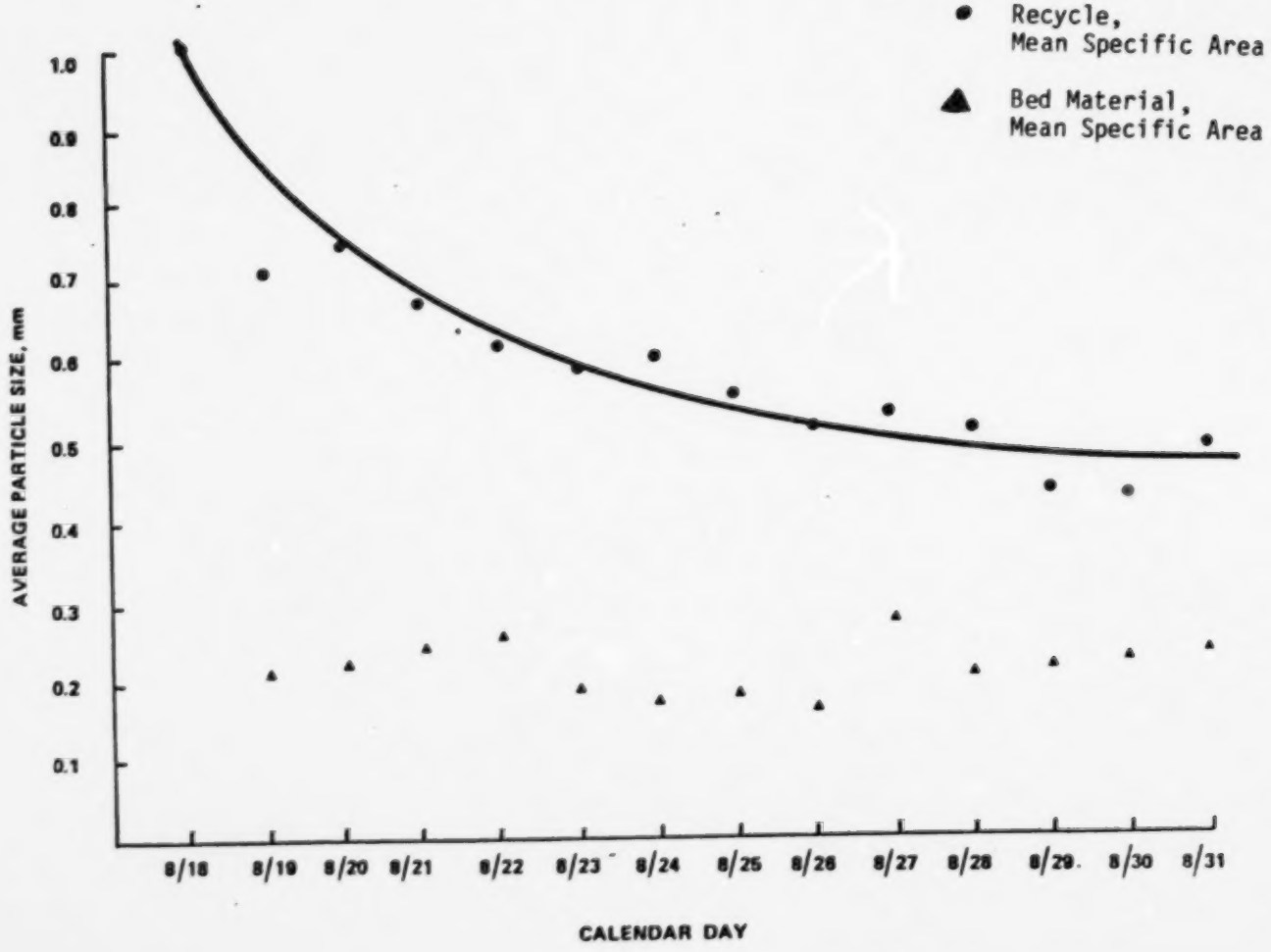

Figure 22. Particle size in bed and at exit of recycle cyclone, 300 hour test.

function of time. The rapid drop in bed particle size at the beginning of the test, followed by a more gradual decline, correlates with the manner in which heat transfer coefficients increased, as shown in the section on Bed Heat Exchangers. Note also that the declining particle size did not seem to affect the cyclone inlet or outlet particle loading defined in "Particulate Sampling Results" (page 46). Other observations from the sieve analysis of the bed material samples are as follows.

1. All bed samples throughout the test showed great similarity to each other. In each sample there were some large pieces accounting for less than 1% of the bed weight. These large pieces, between 6 mesh and 1/2" size, consisted of slag-like particles and glass, pieces composed of grains of original bed material cemented together, and pieces of metal.

2. Rounded pieces of glass in the bed samples were visible in the 12 mesh size in addition to the +6 mesh. Glass could not be seen in the smaller size fractions, although it could have existed.

3. The bed was reddish in color, only slightly darker than the original material.

The fluid-bed material was analyzed for elemental composition. The analysis covered tests for 22 different elements for each of the 13 days of testing. Complete results are contained in a summary below:

1. The Si, Al, K, and Ba content of the bed materials were essentially constant through the 300 hours of testing. The slight decreases in concentrations are due to the accumulations of other elements.

2. There was an accumulation of Ca, Fe, Mg, Ti, Na, Cu, Mn, P, Zn, and possibly Pb in the bed materials during the test. To illustrate, a table of the early test and late test compositions of the bed is shown below. Only the major and minor elements are listed. Trace elements are not included.

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[3]Particle size is calculated by the "Mean Specific Surface" method, as defined in Kunii, D., and Levenspiel, O., Fluidization Engineering, John Wiley and Sons, 1979.

Element	Concentration Weight % 8/18/79	8/31/79
Si	36.0	33.8
Al	4.9	3.8
Ca	0.62	5.5
K	3.5	2.7
Na	1.4	4.0
Fe	0.30	1.2
Mg	0.073	0.69
Ti	0.029	0.28
Ba	0.14	0.10

The bed depth specified for this test was 3-1/2 ft ± 1/2 ft. This depth was necessary to assure that the water tubes in the fluid bed remained covered even with the bed in the slumped condition. Bed depth can be estimated during testing by the pressure drop across the fluidized bed. For Monterey 16 mesh sand, CPC experience has shown that a pressure drop of 16 inches of water column (IWC) per foot of bed is representative.

During the first day of testing there was a net loss of bed material. To make up for the loss, a small amount of Monterey 16 mesh sand was fed in with the fuel. After the first day of testing, the bed slowly increased such that bed material had to be drained once or twice daily. By the end of the test, 1478 lbs of material had been removed at the combustor. One can observe the bed ΔP slowly increasing over a number of hours, then suddenly dropping. The drop occurs as the operator drains bed material as a simple maintenance function during operation. The typical range of bed ΔP was 57 to 63 IWC with an average of 61 IWC. Post-test measurements showed the average pressure drop per foot of bed had changed from 16 IWC per foot to 13 IWC per foot. Some change such as this can be understood if one assumes the bed particle size and composition shifted during testing. This means that the average bed depth increased from about 3.8 feet early in the test to 4.7 feet at the end of testing. At what rate this occurred is not known, but the deeper bed could have accounted for the lower freeboard temperatures (less afterburning) later in the test, as shown in "Process Temperatures" (p. 31).

Recycle Material. The average particle size of the recycle material remained fairly consistent at an average of .25 mm throughout the 300-hour test. Recycle particle size is plotted in Fig. 22.

Figure 23 shows the recycle circulation rate as a function of time. The recycle rate is calculated using the reported gas flows and particulate loadings at the cyclone inlet and outlet. The solids circulation rate ranges between 8 and 25 lb/min, with an average of 16 lb/min. Note that the solid-waste fuel generates ash at a rate of .9 to 1 lb/min. The recycle cyclone maintains a high inventory of fines circulating in the combustor system.

Baghouse Material. 16,990 lbs of material were removed at the baghouse during the 300-hour test. Compared with the 1478 lbs of material removed at

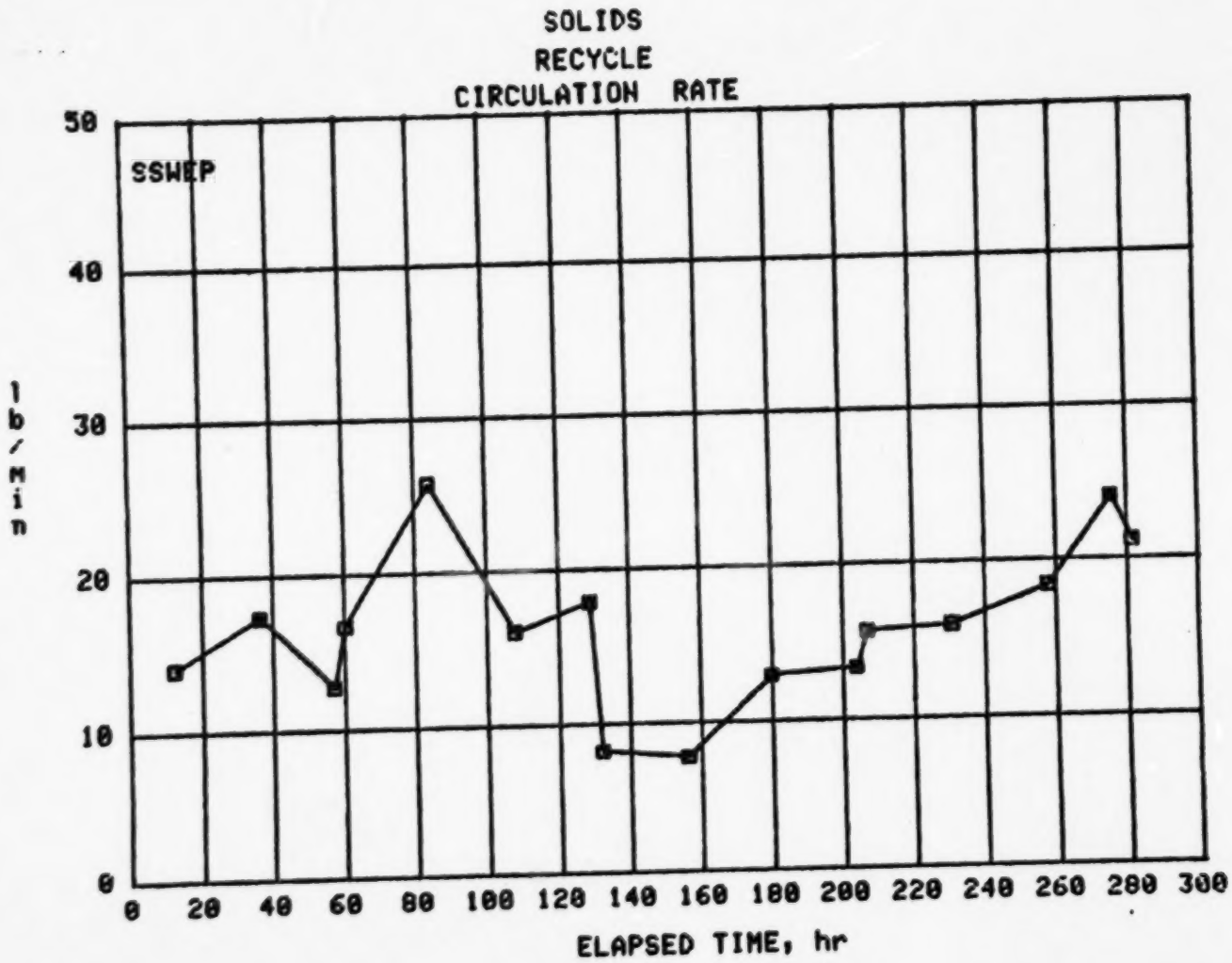


Figure 23. Recycle circulation rate of solids, 300 hour test.

the combustor, it is apparent most of the ash escaped through the exhaust ducting.

Daily samples of baghouse material were analyzed for ash content by CPC per ASTMD-3174. Per this standard, ash is defined to be the portion of the sample remaining after heating the material to 750° C and holding it there for one hour. The ash portion ranged between 97.6% and 98.3%, and averaged 97.9%. The remaining material is comprised of combustibles averaging 2.1% and ranging between 1.7% and 2.3%.

The composition of the ash reaching the baghouse was relatively constant through the test, including the soluble Cl and SO_4, except for a slight decrease in Al content and some variations in Zn, Pb, and CU content.

The major elements composing the baghouse ash are listed below:

Element	Concentration of Weight % 8/22/79	8/31/79
Cl	1.14	1.13
SO_4	0.31	0.47
Si	25.0	24.0
Al	7.8	7.3
Ca	5.9	6.3
K	3.0	2.8
Na	3.5	3.5
Fe	2.4	2.2
Mg	1.3	1.2
Ti	1.1	1.1

Analysis of Corrosion Tube Specimens

Fluid Bed Specimens. Corrosion samples of typical boiler tube materials were mounted in the fluid bed as shown schematically in Fig. 3. Figure 24 shows a plot of the cooling-air temperature at the outlet of the fluid-bed corrosion test specimen. At the 135th test hour, the specimen failed and the cooling air was shut off. The failure appeared to be mechanical and unrelated to corrosion, but as the specimens remained in the fluid bed for the remainder of the test, no useful corrosion data were available.

Freeboard Tube Specimens. A hairpin-shaped tube composed of 2"-long samples of typical boiler-tube materials was installed in the CTU combustor-outlet ducting. The tube was arranged horizontally, with the gas-facing side on the bottom. The 180° bend in the tube was made of stainless steel. Although the composite specimen tube was not mounted precisely in the combustor freeboard, it was exposed to the freeboard gas at freeboard temperatures of 1500-1600 F. Figure 2 shows the relative location of the specimens. The tube was air cooled to a tube metal temperature averaging 717 F throughout the 300-hour test, as shown in Fig. 25. The gas velocity past the corrosion specimens

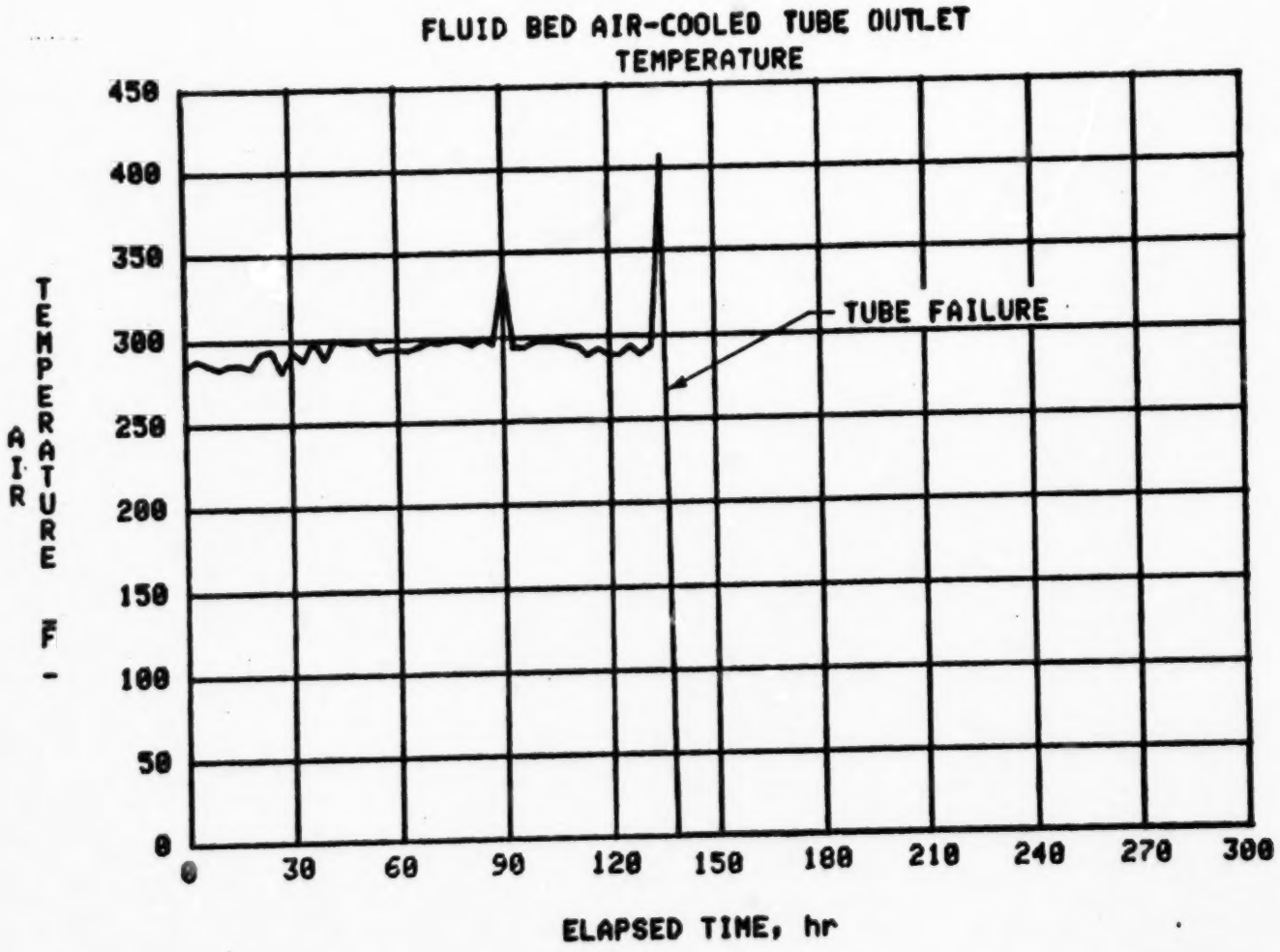


Figure 24. Exit temperature of air from bed corrosion sample tube, 300 hour test.

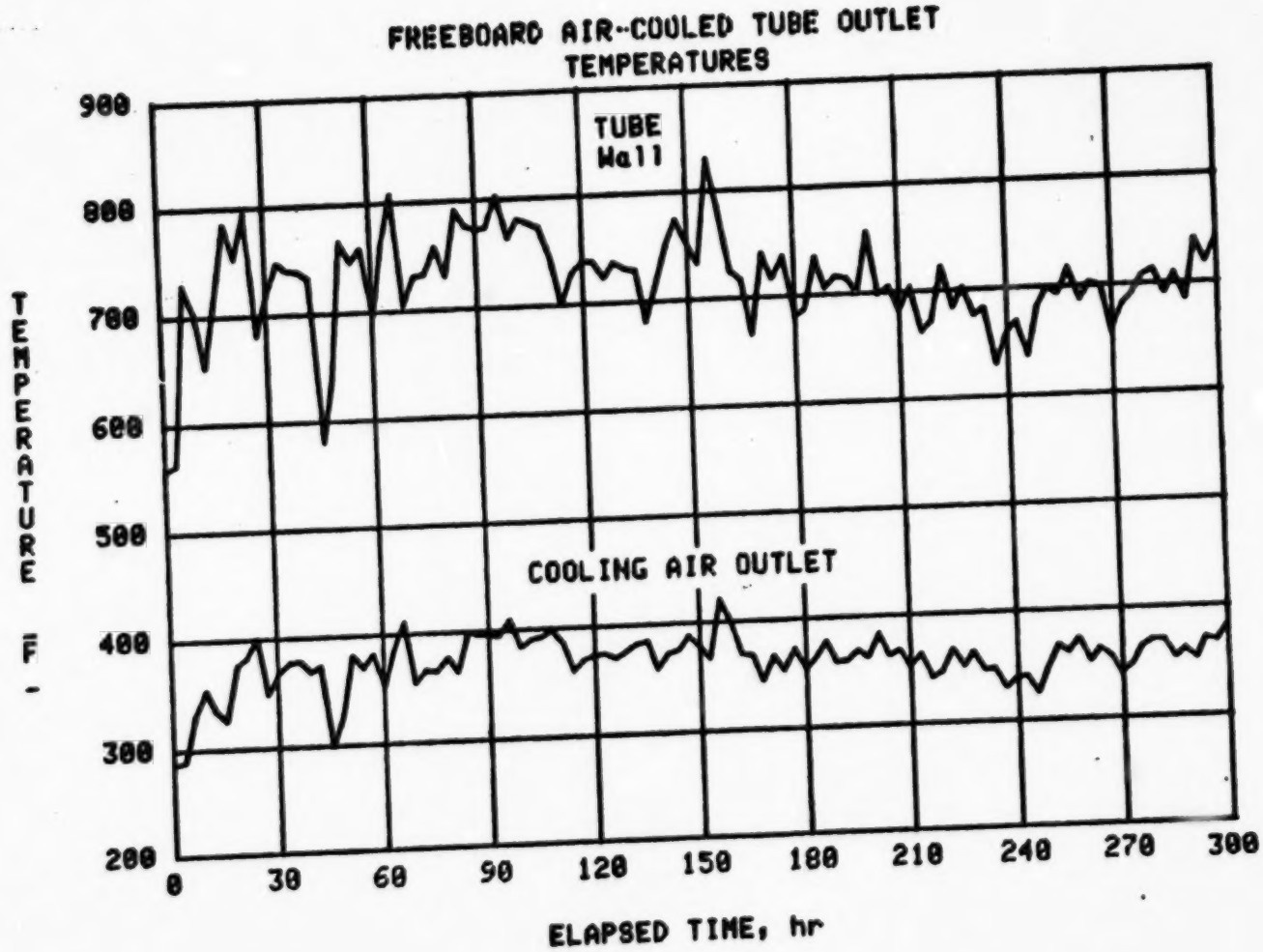


Figure 25. Freeboard corrosion sample tube temperature, 300 hour test.

averaged 35 fps on the basis of total flow over total area. In addition, the particle loading was quite high due to the recycle cyclone, averaging 40-45 gr/acf (see "Fluid Bed Material", p. 46 on recycle).

As shown in Table 6, metal wastage was greatest for the two carbon steel coupons exposed in the freeboard. After approximately 300 hours of operation, wastage was 50-60% of the wall facing the gas side, while wastage of the sides and tops was less than 5%. Wastage was considerably less for the low-alloy steels in the same orientation. On the bottom side, the side facing the gas flow, the wastage was 13-17%, while on the top and sides it was less than 3%. The metal wastage of the austenitic specimens (SS304, SS316, and Incoloy 825) was the lowest, being less than 6% on the side facing the gas flow and less than 1% on the sides and top. Scaling and deposits were also orientation-dependent, with bottoms of the coupons relatively free of scale and deposits compared to the sides and top. As expected, scale formation was thickest on the carbon steels, and the chrome-containing austenitic steels were resistant to scaling.

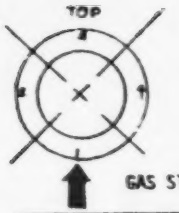
Residual corrosion penetration was very low on the bottoms of the carbon steel and low-alloy specimens. Apparently, corroded areas and scale were removed by erosion as they formed, i.e., corrosion-erosion was a major factor in the metal wastage. Corrosion penetration on the low-alloy specimens was comparatively low on the tops and sides at 5-10 microns. With respect to corrosion under the exposure conditions, the low-alloy specimens compared well with the type SS316 that showed only 5-10 microns of corrosion penetration, while the metal wastage of the low-alloy specimens was greater. The SS304 and Incoloy 825 showed corrosion penetrations ranging from 10-50 microns.

Apparently, corrosion was by oxidation and sulfidation, as sulfur was found in most corroded regions of all coupons. The role of chlorine in corrosion was not determined. The compositions of the corroded and other regions of the various coupons based on KEVEX (X-ray dispersion) analysis are summarized in Table 7. The compositions in Table 7 are for local regions found in the Scanning Electron Microscope (SEM) micrographs shown in for the carbon steel, 1 1/4 Cr-1 1/2 Mo-Si, and type SS316 specimens, respectively. The metal wastage in the carbon steel specimen is obvious. The orientation of the scale and crust formation can also be seen. From SEM analysis, of which the remaining micrographs are contained in Appendix H, and from the KEVEX examination, the following observations can be made:

1. Silicon precipitated in the grain boundary of the base metal in the carbon steel and low-alloy steel.

2. In a few coupons, sulfur was detected in the inner part of the base metal (matrix), with manganese as a dark spot. This was presumed to be a manganese sulfide inclusion and was present in the original metal before exposure.

Table 6
PIPE THICKNESS AND MICROGRAPH MEASUREMENTS
SSWEP: 300-Hour Test Coupons
Location: CTU Freeboard



Specimen Identification	Pipe Orientation	Pipe Thickness (Inch) Unexposed*	Exposed	% Wastage	(Residual Maximum) Micrograph Measurements Scale	Penetration M	Comments
1A1	1. Bottom	.115	.060	47.8	None(a)	6	(a) Corrosion-erosion
(Carbon Steel)	2. Left Side	.112	.113	-.9	15	10	
(SA-106B)	3. Top	.110	.116	-5.5	16	60	
(SA-210A1)	4. Right Side	.113	.110	2.7	(b)	14	(b) Spalled
**2A2	1.	.116	.043	62.9	(a)	<2	(a) Corrosion-erosion
~~(5Cr-½ Mo)~~	2.	.124	.120	3.2	75(b)	50	(b) High S
~~(SA-335P5)~~	3.	.118	.124	-5.1	15	30	
~~(SA-213T5)~~	4.	.120	.116	3.3	200(c)	10	(c) Scale and ash deposit
~~Carbon Steel~~							
3A3	1.	.116	.100	13.8	3	<2	
(1¼Cr-½ Mo-Si)	2.	.115	.116	-.9	60	10	
(SA-335P11)	3.	.118	.124	-5.1	15	10	
(SA-213T11)	4.	.120	.117	2.5	250(a)	10	(a) Scale and ash deposit
4A4	1.	.135	.113	16.3	80	<2	
(2¼Cr-1 Mo)	2.	.130	.129	.8	a.	5	a. Spalled
(SA-335P22)	3	.129	.131	-1.6	b.	10	b. Spalled
(SA-213T22)	4.	.132	.132	0	c.	5	c. Spalled
5A5	1.	.105	.100	4.8	-	35	.005" wastage
(18Cr-8Ni)	2.	.105	.105	0	100(a)	50	(a) Scale and ash deposit
(SA-312-TP304H)	3.	.105	.106	-1.0	(b)	10	(b) Spalled
(SA-213-TP-304H)	4.	.104	.104	0	200(c)	10	(c) Scale and ash deposit
6A6	1	.107	.101	5.6	8	-	.006" wastage
(18Cr-12Ni-2Mo)	2	.118	.118	0	30	10	
(SA-312-TP316H)	3	.107	.107	0	a.	-	a. Spalled
(AS-213-TP-316H)	4	.106	.106	0	b.	5	b. Spalled
7A7	1	.112	.109	2.7	20	30	.003" wastage
(Ni-Fe-Cr-Mo-Cu)	2	.113	.113	0	a.	30	a. Spalled ?
(INCO 825)	3	.117	.117	0	b.	4	b. Spalled ?
(Sb-163)	4	.118	.119	-.8	c.	25	c. Ash deposit

* Unexposed pipe remnant measurements.

** This Specimen was mis-identified and found to be Carbon Steel instead

Table 7
APPROXIMATE COMPOSITION AT DIFFERENT REGIONS OF COUPONS EXPOSED IN FREEBOARD

Photo ID	Orientation	Region/ Area	Kevex Integration Approximation By weight % Mo	Cu	Ni	Fe	Cr	S	P	Si	Other	Remarks
1A1-B4	Top (No.3)	Scale				94.6		0.7	4.0	0.7		
		Dark Area				96.2		0.6	1.7	-	Mn 1.6	Trace of Cl detected
											Mo 0.9	Misidentified Alloy
2A2-D1	Bottom(No.1)	Basemetal	-			99.1	-				Mn 0.3	
3A3-F1	Bottom (No.1)	Basemetal				97.5	1.6	0.2	0.3	0.05		
		Scale				93.7	3.1	1.0	0.2	0.9	Mn 1.1	
3A3-F2	Left Side (No.2)	Scale				95.2	2.0	0.5	0.9	1.0	Mn 0.4	
3A3-F3	Top (No.3)	Scale				97.4	1.2	-	-	1.4	-	
		Dark Area				88.2	8.3	0.6	1.9	1.0		Trace of Ca detected
3A3-F4	Right Side (No.4)	Scale				96.6	1.9	0.9	-	0.6		
		Dark Area				93.4	4.4	1.4	.017	0.8		
4A4-H1	Bottom (No.1)	Basemetal	2.1			93.7	3.4	*	0.2	0.6		
		Scale (Dark)	-			88.7	9.9	*	-	1.2		* Mo interfers the
		Inter Scale	1.5			93.1	4.7	*	.4	.3		detection for S
		Dark Spot	0.6			84.7	3.5			11.1		
4A4-H3	Top (No.3)	Gray Area	1.7			92.7	3.7		1.6	0.3		
5A5-H1	Bottom (No.1)	Basemetal			5.9	67.4	26.2	.04	-	0.5		
		Gray Area			5.8	32.0	59.9	1.0	-	1.3		Trace of Cl Intergranular Attack
		Dark Spot			5.1	59.5	25.6	8.8	0.3	0.5	Mn ≈ 7	MnS inclusion (Mn not intergrated)
5A5-H3	Top (No.3)	Dark Spot			4.2	58.0	26.5	11.1	0.1	.04	Mn ≈10	MnS inclusion (Mn Not integrated)
		Dark Area			4.5	51.2	22.3	4.8	-	17.2	Al ≈	Trace of Na (Al & Na) Not integrated.
6A6-F1	Bottom (No.1)	Basemetal	6.1	-	6.6	62.1	24.8		-	0.3		
		Scale	*	0.3	8.4	24.9	59.5	@ 5.4	-	1.5		* Mo not integrated in order To detect S
7A7-D1	Bottom (No.1)	Basemetal	2.3	-	34.4	29.2	33.7	-	-	0.3		

@ This value maybe higher due to Mo interference.

Based on the 300-hour test, the austenitic steels show the best prospect for superheater service in the freeboard of a fluid-bed combustor. It should be emphasized, however, that 300 hours is not a long time when corrosion is being defined. The material that survives the best for 300 hours may not survive the best after 1000 hours or 8000 hours. The three austenitic alloys are rated as the best prospect because the erosion-corrosion rates on the gas-facing surface were lowest, the scale formation was lowest, and the corrosion penetration was low. The only concern with this class of alloys was the moderate corrosion penetration on the Incoloy 825.

Obviously there is an abrasion problem in the gas-facing side that must be dealt with. It is expected that abrasion can be significantly diminished by lowering particulate concentrations, lowering gas velocities, or incorporating abrasion shields.

The low-alloy steels rate below the austenitic steels for superheater service (approximately 700 F of wall temperature) based on the 300-hour test. These steels exhibited scaling, of which some spalled off. This scale is a form of corrosion. Where it remains attached to the metal surface, the heat transfer is lowered due to the high thermal resistance of the scale. Where the scale spalls off and subsequently reforms, the result is metal wastage. The erosion-corrosion on the gas-facing side could be diminished by design. Nevertheless, metal wastage on the low-alloy steels was higher than on the austenitic steels, and this tendency must be considered.

Carbon steels showed the highest metal wastage due to corrosion-erosion, the highest scaling, and significant corrosion penetration. They generally appear unsuitable for service under the conditions of the 300-hour test.

3.3.3 Conclusions of 300-Hour Test

Successful completion of the 300-hour test demonstrates the feasibility of fluidized-bed combustion of municipal solid waste to generate steam. Necessary conditions for steam generation were met:

- Operation at reasonable low excess air (40-50%) for process efficiency.
- Constant bed temperature (± 20 F) for controllable system output.
- Operation at moderate firing rate, as indicated by a superficial velocity of 4.4 to 4.6 fps.
- Fluidization was smooth throughout the test, with no evidence of deterioration or agglomeration at bed temperatures of 1400 F.
- No combustor and downstream slagging or significant deposits were evident after test completion.
- Water tubes were immersed in the bed to simulate a boiler configuration.

These conditions were met in a long-duration test designed to reveal any process problems likely to develop.

Environmental acceptability is demonstrated by comparing the NO_x and SO_2 emissions against applicable standards. For Palo Alto municipal solid waste, emissions were:

NO_x	(average)	.25 lb/million Btu input,
SO_2	(average)	.06 lb/million Btu input.

High combustion efficiency was shown by low carbon monoxide and hydrocarbon emissions and by a low (2.1%) combustible content in the ash.

The equilibrium-bed media properties depend on the source of the solid waste and the fuel preparation. During the 300-hour test, the average particle size of the bed media decreased significantly, although it appeared to be reaching equilibrium. In addition, the elemental composition of the bed was still changing after 300 hours. Neither situation caused any detrimental change in bed-fluidization properties, nor did it appear to affect particulate loadings.

It has been concluded that the overall heat transfer coefficient for the bed tubes increased during the test because the bed media size decreased. The heat transfer coefficient rose from a value of 45-50 Btu/hr-ft^2-F to reach a steady-state value of 60 Btu/hr-ft^2-F.

Seven selected steels and alloys were exposed in the freeboad for corrosion evaluation. They were installed as air-cooled sections of pipe simulating superheater conditions. All coupons experienced corrosion and metal wastage. The metal wastage occurred in a pattern oriented to the particulate-laden gas flow and was significant for the carbon steels as a result of corrosion-erosion. Metal wastage was less for the low-alloy steels and least for the austenitic steels (i.e., SS304, SS316, and Inco 825). Scaling was also greatest for the carbon steels and least for the austenitic steels. Thus, based upon the conditions of the 300-hour test, abrasion-erosion must be minimized by suitable design, and the austenitic steels appear to have the highest potential for the considered application.

4.0 SYSTEMS STUDY

The purpose of the present study was to perform a technical and economic evaluation of a solid waste-fired fluid-bed combustor and co-generation power plant for Stanford University. As discussed in Section 2.0, the concept of this plant was to process solid waste at a site remote from the Stanford campus and to transport this processed waste, which would be sized to pass through holes approximately 4" square, to a location on campus. The solid waste would be burned in a fluid-bed combustor with tubes in the bed and in the freeboard to generate steam for heating purposes on the Stanford campus. The pressure of this steam system would be sufficient so that expansion would occur in a turbine before the pressure was reduced to that for the steam-heating system. If all of the steam were not required for heating, a low-pressure turbine could also generate electric power. The size of this system was determined by the expected available solid waste in 1983. After processing, it was estimated that 800 tons per day would be available at the Stanford campus.

The scope of the present study was to prepare a conceptual design in sufficient detail to define the system and estimate the cost, to specify major equipment and processes for a Class II estimate (20% accuracy), to review the energy usage at Stanford University, to provide co-generation of heating steam and some electricity, and to review the test data from the experiment described in Section 3.0 to provide an estimate of the plant emissions for the proposed plant.

In order to determine the size of the components, it was necessary to study the energy load of Stanford University. An average "summer day" and an average "winter day" were selected from available records and were used to specify load profiles. These average days, rather than an integration over the year, were used to determine the performance requirements for the plant and the economics of the plant. As described below in Section 4.2, the heating load for the University is always taken care of by the projected plant, but the electric power output is inadequate for all of Stanford's needs. Therefore, some power would have to be purchased from the utility.

A very simple cycle was assumed for the plant, and it is anticipated that improved performance and considerable savings in cost could be effected by optimization or by relaxing some of the constraints. For example, a heat exchanger was interposed between the boiler turbine system steam and the heating lines of the University. On further study, it may prove possible that return water from the Stanford heating system may be treated and used as boiler-feed water so that this expensive and inefficient heat exchanger could be removed. The decision to produce all of the heating steam required for the University and only part of the electrical energy was an arbitrary one. It may be better, on closer study, to operate the existing steam plant for certain periods

of the day and to produce more electrical power, in order to reduce the amount of purchased power from the public utility.

The design criteria used in specifying the plant were these:

1. A site was selected near the existing Stanford University heating plant in order to minimize the steam-line interconnection link.

2. The plant size was based on the projected supply of municipal solid waste at the time of plant completion in 1983. (It was estimated that 1200 tons per day would be available as raw solid waste and that 800 tons per day of processed solid waste would be transported to the campus.)

3. Moderate steam conditions of 600 lb/in^2 and 750 F were selected in order to diminish the possibility of boiler-tube corrosion due to combustion of the solid waste.

4. Emphasis was placed on a "good neighbor" design for a campus location so that minimal architectural impact would be made.

5. All applicable environmental standards must be met by the projected plan.

In the sections which follow, we first describe the thermodynamic cycle and the results of the thermodynamic analysis. Then the system sizing and system components are described, followed by a discussion of the general plant layout and design. The emissions estimated for the plant are given based on the performance of the tests described in Section 3.0. The section ends with a discussion of the economics of the total plant.

4.1 Thermodynamic Cycle

The steam-flow system is diagrammed in Fig. 26, where it is seen that a fluid-bed boiler is used to generate superheated steam to operate both an extraction and a condensing turbine which drive an electrical generator. The extraction steam at 170 psia pressure is condensed in a heat exchanger in which processed steam used for heating of Stanford University buildings is vaporized at 140 psia. The condensate from the extraction steam is returned to the boiler, and the loop for the boiler-turbine steam is separate from that of the process steam. Steam which is not used for heating continues to the condensing turbine and, after exhausting from this turbine, is condensed by cooling water which is provided by a cooling tower.

As mentioned, the maximum temperature of the steam was chosen to be 750 F and the pressure 600 psig. The 750 F steam temperature requires a maximum metal temperature of approximately 800 F. The conditions of the steam and the flow rates of the various fluids are shown in Table 8. The flowrate figures are based on the maximum 1000 tons per day firing rate, although the average firing rate for the 24-hour day would be at the rate of 800 tons per day. The properties of the processed MSW were taken from data obtained during the

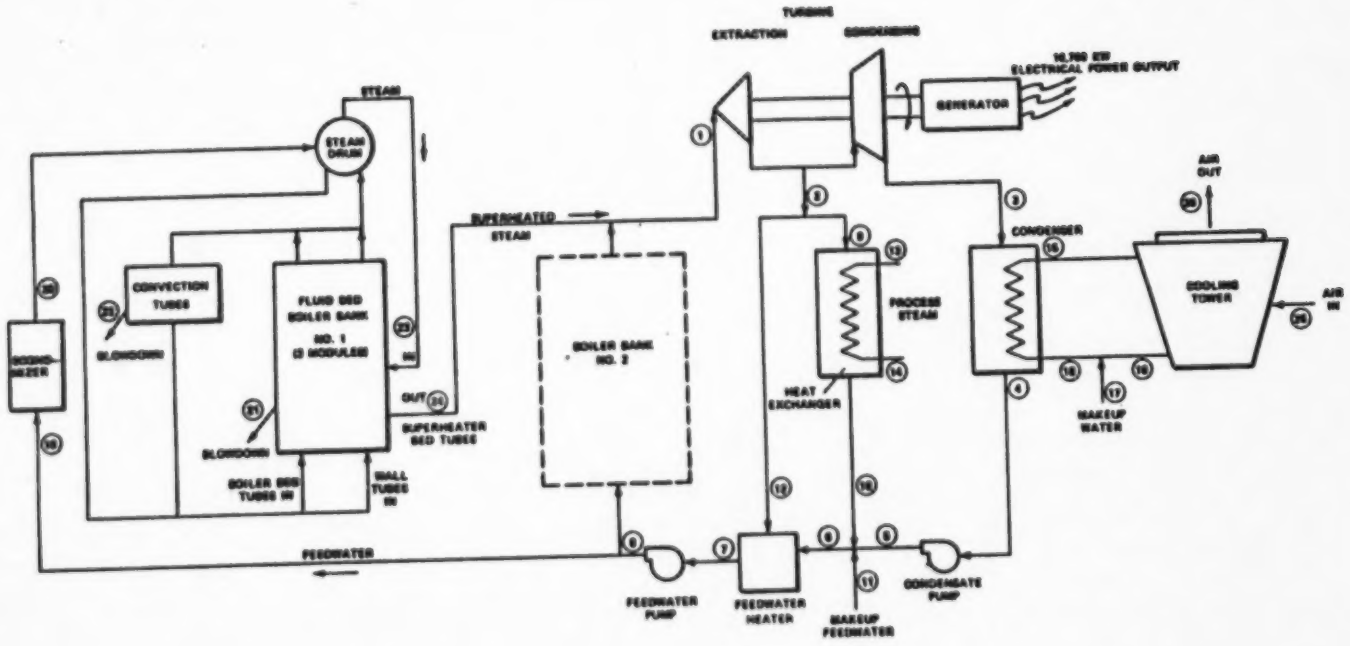


Figure 26. Steam flow diagram--Stanford solid waste energy plant.

Table 8

STEAM FLOW AT 1000 TPD FIRING RATE

Station	Flow (lb/min)	Pressure (psia)	Temp. (F)	Comment
1	4164	615	750	Steam turbine inlet
2	2022	170	481	Extraction flow
3	2142	2	126	Exhaust flow
4	2142	2	126	Condensate
5	2142	170	127	Condensate pump outlet
6	4078	170	237	Feedwater heater inlet
7	4248	170	278	Feedwater heater outlet
8	4248	675	280	Feedwater pump outlet
9	2852	170	481	Heat exchanger inlet
10	1852	170	368	Heat exchanger outlet
11	84	170	60	Boiler makeup water
12	170	170	481	Steam-to-feedwater heater
13	1521	140	125	Process-steam return
14	1521	140	353	Process steam
15	96529	0(psig)	110	Condenser water outlet
16	94696	0(psig)	91	Cooling-tower water outlet
17	1833	0(psig)	60	Cooling-tower makeup water
18	96529	0(psig)	90	Condenser water inlet
19	2124	675	278	Economizer water inlet
20	2124	665	440	Economizer water outlet
21	30	665	497	Wall tubes blowdown
22	11	665	497	Convection tubes blowdown
23	2082	665	497	Steam superheater inlet
24	2082	615	750	Steam superheater outlet
25	406196	0(psig)	80	Cooling-tower air inlet
26	108029	0(psig)	100	Cooling-tower air exhaust

Note: Stations 19 through 24 for one boiler bank composed of three module fluid-bed boilers and one each stream drum, convection tubes, and economizer.

experimental phase of the present program. Average fuel properties are moisture 30%, ash 24.4% dry, carbon 50.5% dry inert free, hydrogen 6.8% dry inert free, oxygen 42.7% dry inert free, higher heating value 8640 Btu/pound dry inert free.

For the calculations made, a condenser pressure of 2 psia was assumed and a boiler blow-down loss of 2% was also assumed.

4.2 System Sizing

The system was sized by estimating the available municipal solid waste in North Santa Clara County that might be available to Stanford University in 1983. This figure was taken to be 1200 tons per day, and after processing so that the solid waste could be handled pneumatically through 5-inch lines, the available solid waste was estimated to be 800 tons per day. No attempt was made to define in detail the solid waste-processing scheme, but a minimum energy system is recommended. As demonstrated in the tests of Section 3.0, it is not necessary to produce a pelleted RDF of high quality.

The steam and electric loads for Stanford University were studied, and an average summer day and an average winter day were selected. The usage was increased to be appropriate for 1983, and a decision was made to supply all of the steam requirement for the University and to produce as much electricity as possible after the steam requirement was met. This decision was not entirely arbitrary, because it was hoped that air-pollution credit could be obtained if the present Stanford heating system were shut down. With this credit, there would be no problem with the projected system's meeting the strict Bay Area air-pollution control standards.

In Table 9 is shown the steam and electricity demand for the University and that available from SSWEP, based on 800 tons per day of processed solid waste at the University. It is seen that the steam demand is met completely and that the power demand is only partially met. Electricity would be purchased from the local utility to make up the difference. Also seen in the table is the firing rate of processed MSW as a function of time of day. For the summer period, it is seen that the turn-down ratio of the plant is approximately 2:1, and this is not considered excessive for the fluid-bed combustor system planned.

It should be pointed out that electrical power standby is required on the University campus, particularly for the Stanford University Hospital. Therefore, an interconnection with the public utility would be necessary, and a standby fee would be paid in order to provide this service for the University, including the Hospital.

No optimization was made for the firing rates and no investigation of the availability of municipal solid waste from communities other than those in the North Santa Clara County JPA was undertaken. A somewhat larger system may show considerable economic advantage if purchased power is reduced.

Table 9

STANFORD ENERGY REQUIREMENTS
(Daily averages, 1982-1983 fiscal year)

Time	Demand		SSWEP Supply		SSWEP Firing Rate	Purchased Electricity
	Steam (1000 lb/hr)	Electricity (MW)	Steam (1000 lb/hr)	Electricity (MW)	(TPD of MSW)	(MW)
Summer						
0100-0800	73.0	12.0	73.0	4.9	554	7.1
0800-1000	75.2	16.1	75.2	13.0	1000	3.1
1000-1200	86.8	18.4	86.8	12.2	1000	6.2
1200-1900	94.5	18.7	94.5	11.7	1000	7.0
1900-0100	78.0	14.9	78.0	7.7	719	7.2
Summer average	81.9	15.6	81.9	8.9	800	6.7
Winter						
0100-0600	128.5	9.5	128.5	1.9	600	7.7
0600-0800	180.6	11.1	180.6	2.8	839	8.3
0800-1200	164.0	17.8	164.0	5.5	923	12.3
1200-1600	143.2	18.3	143.2	7.3	923	11.0
1600-2100	140.6	17.3	140.6	6.6	923	10.7
2100-0100	104.8	14.0	104.8	2.0	628	12.0
Winter average	139.8	14.9	139.8	4.5	800	10.4
Average for year	110.8	15.3	110.8	6.7	800	8.6

4.3 Component Design and Cost Estimating

The plant design was broken down into 12 major components, as listed below:

1. Boiler system
2. Start-up system
3. Combustion air system
4. Flue gas system
5. Bed-maintenance system
6. Flyash-disposal system
7. Fuel-feed system
8. Fuel receiving and storage
9. Main steam system
10. Feed-water system
11. Electrical and control system
12. Buildings and site

For each of these systems, sufficient design work was done to define a concept and to specify the necessary size of the equipment. We see that the total boiler arrangement includes six modules with integral recycle cyclones. The dimensions are indicated and are based on the results from the experiments described in Section 3.0. For this system the length of piping, the size of piping, the number of valves, and the number of pounds of steel were estimated.

The cost was arrived at after considering the materials cost, the freight involved for these materials, the shop labor, the erection labor at the site, the cost of rentals such as cranes, and finally a contingency. Where standard components were used, cost estimates from vendors were obtained and quotations for components such as fans, electric motors, steam turbines, electrical switch gear and controls were obtained. A layout was made for the equipment arrangement. Buildings were designed to house this equipment and to receive the processed municipal solid waste. The buildings were designed to be compatible with the environment of the Stanford University campus, and costs were included for grading roads, landscaping, and similar items. No cost was included for the value of the land.

Table 10 lists the major components considered in the design, along with the principal items contributing to the cost. From experience gained at Combustion Power Company in estimating costs for products manufactured there, it is estimated that the cost of the present system is accurate within ± 20%. It should be pointed out that optimization was not performed and that this would be expected to reduce the costs from those given in Section 4.6.

4.4 Plant Design

The general concept of the plant, which is shown schematically in Fig. 1, is illustrated in plan view in Fig. 27. It is seen that this layout requires three buildings, a fuel-receiving building, a boiler building, and a turbine building. An artist's rendition of what this arrangement might look like is

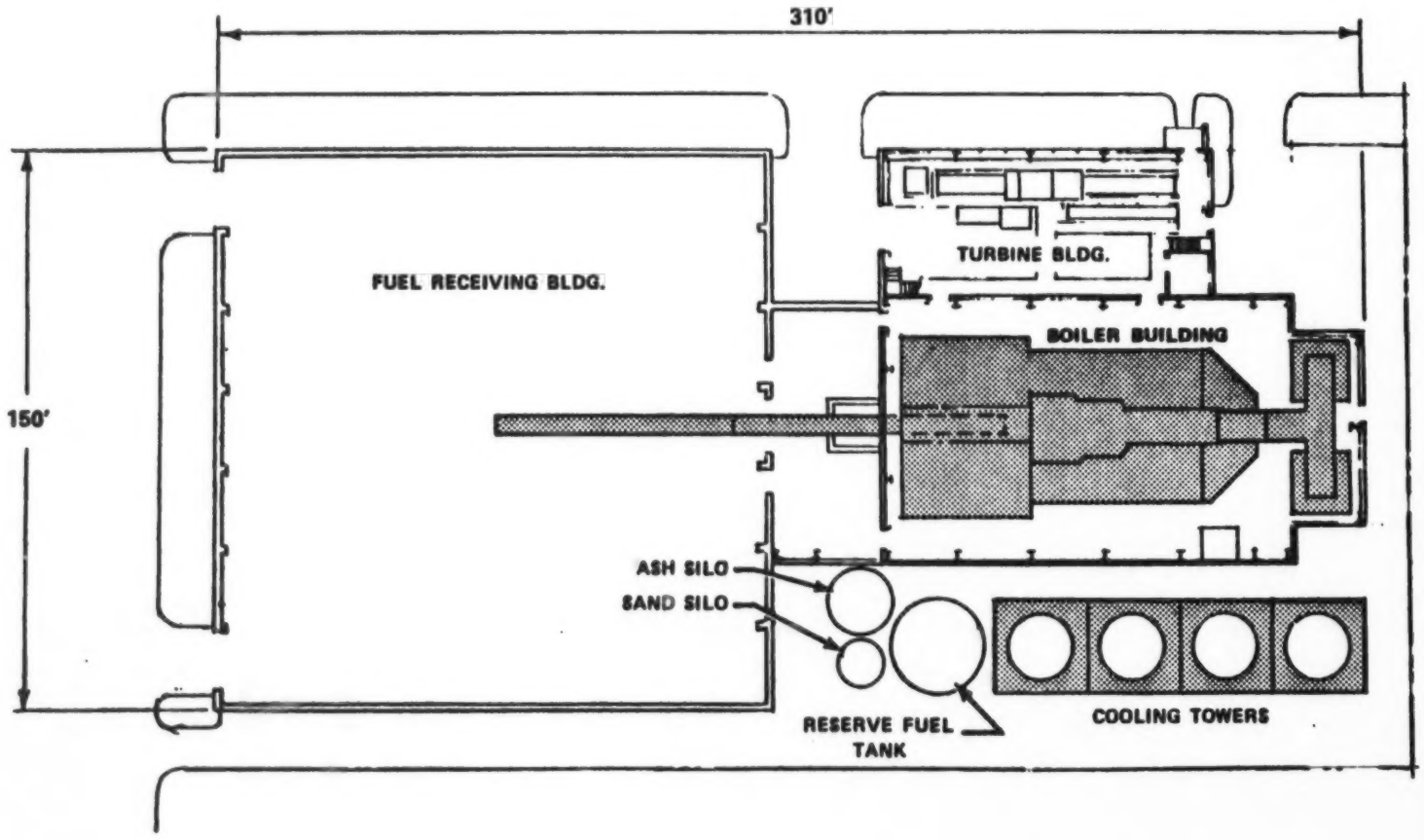


Figure 27. Site plan--Stanford solid waste energy plant.

Table 10

PLANT DESIGN - LIST OF MAJOR EQUIPMENT

1. Boiler System
   - Modules w/tubes & plenums (6)
   - Recycle cyclones (24)
   - Exhaust manifolds (2)
   - Evaporators (2)
   - Economizers (2)
   - Attemporators (2)
   - Supports & lagging
   - Sootblowers (6)

2. Start-up System
   - Duct-burner assembly
   - Booster fan
   - Fuel-oil pumps (dual)
   - Fuel-oil storage tank
   - Bed injectors (36)
   - Air manifold & dampers

3. Combustion Air System
   - F.D. fans & motors (2)
   - Intake silencers (2)
   - Tubular air preheaters (2)
   - Ductwork

4. Flue-Gas System
   - Multiclones (2)
   - Electrostatic gran. filter
   - I. D. fan & motor
   - Ductwork

5. Bed-Maintenance Systems
   - Slide gates (6)
   - Water-cooled conveyors (2)
   - Blowers w/filter silencers (3)
   - Airlock feeders (3)

5. Bed Maintenance Systems (cont.)
   - Sand-storage bin
   - Bin discharger
   - Fabric filter
   - Transport piping
   - Discharge diverter valves (7)

6. Flyash Disposal System
   - Airlocks (6)
   - Screw conveyors (2)
   - Feeders (2)
   - Transport piping
   - Ash silo
   - Fabric filter
   - Blower w/filter/silencer (2)
   - Silo discharger
   - Discharge conveyor

7. Fuel-Feed System
   - Main conveyor
   - Distribution conveyor
   - Feed bins (6)
   - Metering conveyors (6)
   - Conditioners (6)
   - Airlocks (36)
   - Blowers w/filter silencers (2)
   - Transport piping

8. Fuel Receiving and Storage
   - Apron
   - Conditioners
   - Live storage bin
   - Fabric filter w/blower
   - Dust-collection ductwork
   - Front-end loader

9. Main Steam System
   - Turbine & assoc. equipment
   - Condensor
   - Condensate pumps
   - Condensor vacuum pumps
   - Condensate polishing
   - Cooling towers
   - Cooling-water pumps
   - Process heat exchangers

10. Feedwater System
    - Boiler feed pumps (motor) (2)
    - Feedwater heater
    - Deaerating feedwater heater
    - Boiler feedwater transfer pump
    - Deaerated feedwater storate tank
    - Boiler feed pumps (turb.) (2)
    - Feedwater piping valves

11. Electrical & Control Systems
    - Generator & controls
    - Switchgear
    - Transformers
    - Motor control center
    - Instrumentation & controls

12. Buildings & Site
    - Grading & roads, landscaping
    - Foundations
    - Structure
    - Enclosures
    - Maintenance & administration
    - Heating, ventilation, A.C.
    - Fire-safety equipment
    - Utilities

shown in Fig. 28.

The fuel-receiving building is a totally enclosed receiving and storge facility. Transfer of processed MSW is done after building doors are closed, in order to prevent noise or problems with the solid waste material. The building is sized so that a maximum storage capacity adequate for 15 hours of operation is provided. Normally an inventory for six hours' operation is anticipated. The fuel-handling system is very simple and would have maximum reliability. The processed MSW from self-unloading transfer trailers is stored and retrieved by a mobile front loader. Fuel is fed to the boiler by an apron conveyer with a surge bin to provide for a uniform, continuous flow. The cost estimate includes equipment for dust collection and fire suppression.

The boiler building is totally enclosed and contains the fuel-feed system, the fluidized-bed boiler, the forced and induced draft fans, heat exchangers, flue-gas particulate-control equipment, and maintenance platforms, cranes, etc. The fuel-feed equipment is sealed in order to maintain the boiler area as a clean facility.

The turbine building contains a maintenance shop and an administrative office, in addition to the turbine generator, condenser and feed pumps, feedwater system, heat exchangers, control room, and electrical switch gear. The cost estimate provides an overhead crane for maintenance in the turbine area, and the building is separated from the other buildings for maximum cleanliness and personnel comfort.

General performance figures for the plant are shown in Table 11. In order to arrive at the performance figures given above, it was necessary to determine the auxiliary power requirements, which are given in Table 12.

4.5 Emissions

During the course of the tests described in Section 3.0, measurements were made by the Combustion Power Company of a number of possible pollutants. Of particular interest to the system study are those measurements of SO_2, NO_x, CO, and hydrocarbons which are controlled by the Bay Area Air Pollution Control District. On August 29, during the afternoon, engineers from the California Air Resources Board brought portable equipment to the site and made simultaneous measurements with the Combustion Power system operators. Below are reported average data from the CPC instruments and from the CARB instruments. The CPC data are averages for the last 144 hours of the 300-hour test when new recorders were installed, and the CARB data are averages for the one-hour period after a pause in sampling to span their instruments (from 2:24-3:26 pm on August 29, 1979).

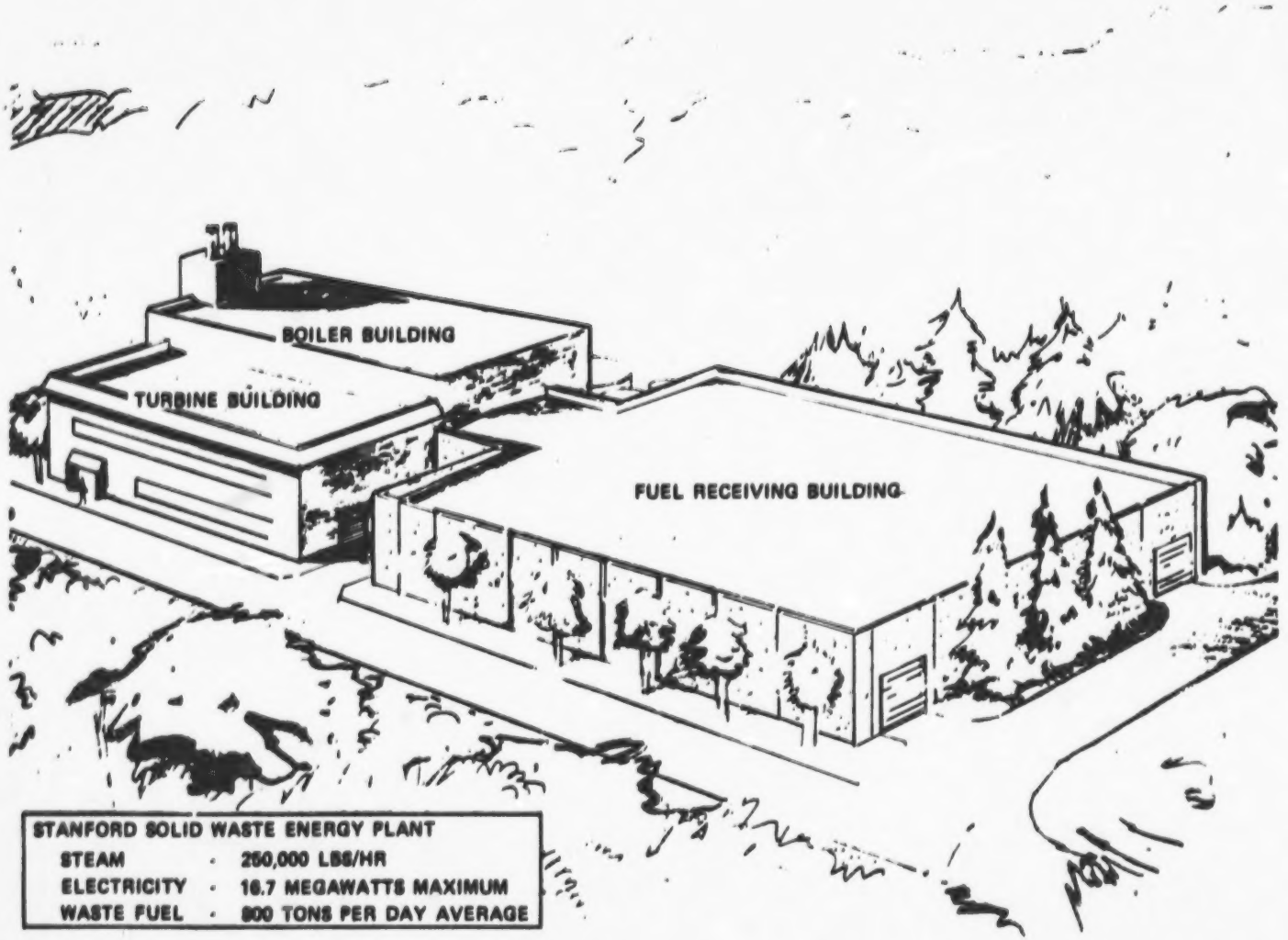

BOILER BUILDING
TURBINE BUILDING
FUEL RECEIVING BUILDING
STANFORD SOLID WASTE ENERGY PLANT
STEAM · 250,000 LBS/HR
ELECTRICITY · 16.7 MEGAWATTS MAXIMUM
WASTE FUEL · 900 TONS PER DAY AVERAGE

Figure 28. Stanford solid-waste energy plant.

Table 11

PLANT PERFORMANCE

- Design Firing Rate for Processed MSW Fuel:

  Average - 800 tons per day

  Maximum - 1000 tons per day

- Yearly Average Plant Output

  Steam at 125 psi, 110,800 lb/hr

  Electricity - 6.7 MW

- Boiler Output: Steam at 600 F, 750 psi

  Average - 200,000 lb/hr

  Maximum - 250,000 lb/hr

- Maximum Electrical Output (net)13.8 MW

  Concurrent 125 psi steam output91,200 lb/hr

- Fuel Storage: Normal: 200 tons (6 hrs average output)

  Maximum: 500 tons (15 hrs average output)

- Reserve Fuel: Low-grade bunker oil - 35 GPM at maximum output

- Reserve Fuel Storage: 126,000 gal, 3 days

Table 12

PLANT AUXILIARY POWER REQUIREMENTS AT MAXIMUM OUTPUT

System	Power (KW)
Boiler	23.9
Startup	7.5
Combustor air	805.4
Flue gas	913.5
Bed maintenance	31.4
Flyash disposal	31.4
Fuel feed	298.3
Fuel receiving	67.1
Main steam	305.7
Feedwater	119.3
Miscellaneous motors	11.2
Lighting and controls	15.1
Miscellaneous losses (9%)	236.7
Total	2866.5

Atmospheric Pollutant Measurements (CPC and CARB)

Pollutant	CPC	CARB
SO_2	29 ppm	58 ppm
NO_x	163	178
CO	204	242
Hydrocarbons	26	5.4

It should be pointed out that the excess air during the CARB measurement period was only 41 per cent. Earlier in the morning of August 29, when only CPC instrumentation was available, the excess air was at 53 per cent, and the observed levels were 160 ppm for NO_x and 100 ppm for CO.

The data above can be reported on a pounds per hour basis using the flow rate of combustion products for an 800 ton per day plant. Below, the CARB data are reported in this form, together with a "credit" that Stanford is permitted to take if it shuts down its present heating plant.* The figures for the credit were taken from a consultant's report to Stanford.

Atmospheric Pollution Projections

Pollutant	Projected 800 T/D Plant	Credit from Existing Boiler
SO_2	2.9 lbs/hr	24.1 lbs/hr
NO_x	7.7	23.1
CO	8.9	5.2
Hydrocarbons	0.7	1.1

It is seen from the above table that, based on experimental data, only CO would exceed the credit available from the existing boiler. The present boiler figures are based on steam generation at the rate of 80,000 lbs/hr and the SSWEP plant figures are based on 800 tons of processed MSW per day, corresponding to 110,000 lbs of steam per hour plus an average of 6.7 MW of electrical power. Thus the SSWEP plant is nearly 40% larger than the present boiler, and the pollutants are very similar. If the data are used for the 53% excess-air case, then the SSWEP plant produces less CO than the present boiler does.

It appears that the fluid-bed combustion of MSW is a sufficiently clean process so that there would be little difficulty in meeting the stringent requirements of the San Francisco Bay Area Air Pollution Control District, because of the offset permitted by the shutting down of the present boiler.

Nothing has been said about particulates at this point because it is considered possible to meet the particulate requirement through the use of an electroscrubber manufactured by the Combustion Power Company or the use of a baghouse manufactured by a number of different organizations.

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*"Stanford Resource Recovery Study," by PBQ&D, Inc./Cosulich, in association with Paine Webber Jackson & Curtis, Inc.

As described in Section 3.0, analyses were made of the bed material during the 300-hour test, and also measurements were made for HCl in the exhaust gas.

4.6 Economic Summary

The material from the cost estimates described in Section 4.3 is summarized in Table 13. Each major subsystem is shown, along with the additional costs which are recommended for a construction project such as this by the standards of the Electrical Power Research Institute. The total direct cost as estimated is 16.7 million dollars, and the total plant investment, using various contingencies and sales tax, amounts to $23.1 million. This figure should be compared to plants which handle 1200 tons per day of raw municipal solid waste and produce both steam and electrical power. The costs presented do not include processing or transporting the processed MSW to the point of use.

Table 13.

STANFORD SOLID-WASTE ENERGY PROGRAM

Total Plant Investment

1.	Boiler system	$2,239,700
2.	Startup system	155,200
3.	Combustion air system	798,900
4.	Flue-gas system	2,382,000
5.	Bed-maintenance system	84,100
6.	Flyash-disposal system	79,200
7.	Fuel-feed system	457,800
8.	Fuel-receiving bldg., equipment	252,400
9.	Main steam system	5,421,000
10.	Feedwater system	1,942,600
11.	Electrical/controls/misc.	1,204,100
12.	Building, sitework, construction, A & E	1,645,000
	Total Direct Costs	16,662,000
	Undistributed Costs (6%)	999,700
	Process Capital	17,661,700
	Engineering & Home Office Fees	1,666,700
	Subtotal	19,327,900
	Project Contingency (Subtotal x 15%)	2,889,200
	Process Contingency (Item 1 x 5%)	112,000
	Sales Tax	777,300
	Total Plant Investment	$23,116,400